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Preface

This dissertation consists of three self-contained chapters that study questions in the fields of international trade and environmental economics.

Chapter 1 examines the effects of carbon taxes and carbon tariffs on emissions and welfare. Although this issue is becoming more pressing, standard models largely ignore the role of heterogeneity in firms' responses. Using administrative German firm data, I show that two determinants of carbon leakage — the emission intensity of production and the import intensity of intermediates — vary significantly across firms. I incorporate this heterogeneity into a model of heterogeneous firms to introduce two new adjustment channels to carbon pricing: the reallocation of production towards firms with a lower emission intensity or a higher import intensity. I calibrate the model to the German manufacturing sector and simulate an increase in the domestic carbon price. A model with firm heterogeneity predicts greater emission reductions, smaller welfare losses, and a higher leakage rate. Production reallocation towards less emission-intensive firms offsets increased emissions from offshoring. Combining a domestic carbon price with a carbon tariff would further reduce leakage and welfare losses. However, it would not yield additional emission reductions since it limits the reallocation of domestic production towards clean firms.

Chapter 2, co-authored with Alessia Campolmi, Harald Fadinger, Chiara Forlati, and Ulrich Wagner, proposes an alternative policy to the EU's Carbon Border Adjustment Mechanism (CBAM) to limit carbon leakage. Carbon leakage undermines the effectiveness of unilateral carbon pricing. Taxes on import-embedded emissions, like the EU's CBAM, prevent leakage but their scope is limited by strong information asymmetries. We propose an alternative system of border tax adjustments, the Leakage-Based Adjustment Mechanism (LBAM), that can be applied to all sectors using readily available data. LBAM tariffs sterilize carbon leakage without requiring information on foreign carbon intensities. Using a quantitative trade model, we show that LBAM improves over CBAM in terms of global emissions and EU welfare. LBAM also avoids large welfare losses among EU trading partners that would result if CBAM was extended to all sectors.

Chapter 3 studies the aggregate effects of energy tax exemptions on output, emissions, and exports in Germany. Energy tax exemptions are a widely used policy instrument to shield energy-intensive, trade-exposed industries from rising energy costs. Using German firm-level data, I document that these exemptions overlap with carbon pricing policies and are applied asymmetrically across firms. This reduces allocative efficiency and undermines domestic emission reductions, although it may mitigate emission leakage. To quantify these economic and environmental consequences, I develop a heterogeneous firms open economy model and compare outcomes under distortionary energy tax exemptions to those under export subsidies, a frequently proposed alternative policy instrument.

1 The Role of Firm Heterogeneity in Carbon Leakage

1.1 Introduction

Without a globally coordinated effort to harmonize carbon pricing, countries rely on domestic policies to reduce carbon emissions. However, rising domestic carbon prices can lead to emission-intensive imports displacing clean domestic production, resulting in carbon leakage.

A growing literature proposes to address this leakage problem by combining a domestic carbon price with a carbon tariff (Campolmi et al., 2024; Farrokhi and Lashkaripour, 2025; Kortum and Weisbach, 2021). These papers commonly use industry-level data and assume that firms differ only in their productivity. This, however, limits within- and between-firm adjustments to climate policies and is at odds with empirical evidence documenting pronounced heterogeneity in two measures of leakage risk at the firm level: a firm's international sourcing activity and emission intensity. Firms select into importing, source from different partner countries, and import different products (Antràs et al., 2017; Bernard et al., 2009). In the context of trade liberalization, this heterogeneity has important implications for aggregate welfare, productivity, and employment (Blaum et al., 2018; Halpern et al., 2015; Hummels et al., 2014). Similarly, there is significant heterogeneity in firms' emission intensities and fuel mix within and across industries (Barrows and Ollivier, 2018; Graevenitz and Rottner, 2020; Lyubich et al., 2018). Despite these findings, the role of firm heterogeneity for aggregate outcomes of climate policy has received limited attention (Jo and Karydas, 2024; Kim, 2023; Sogalla et al., 2024), and its implications for carbon leakage remain unexplored.

In this paper, I ask how important firm heterogeneity is for the effectiveness and welfare effects of climate policies. I study this question empirically and theoretically in the context of the German manufacturing sector. First, I show that German firms vary along two dimensions of heterogeneity that shape carbon leakage: their sourcing strategy for intermediate inputs and their emission intensity. Next, I incorporate these two dimensions of heterogeneity into a standard Melitz model with intermediate inputs. Compared to the standard model, this introduces a new adjustment channel: the reallocation of production to firms less affected by climate policies, i.e., those with lower production cost increases. I find that ignoring both sources of heterogeneity leads to an underestimation of the reduction in emissions and an overestimation of the welfare losses associated with an increase in domestic carbon prices. Adding a carbon tariff reduces the leakage rate, but not the total emissions, in a model with heterogeneity in emission intensity and import intensity. A domestic carbon price reallocates production towards low-emission-intensity firms that are import-intensive, decreasing domestic emissions but causing leakage through an increase in imports. Combining a carbon tax and a carbon tariff, however, reallocates production towards high-emission-intensity firms compared to the carbon-tax-only scenario. This increases domestic emissions more than it decreases foreign emissions since the most emission-intensive domestic firms produce more emission-intensively than foreign firms.

The German manufacturing sector provides a particularly interesting setting for this analysis. Germany is the largest emitter in the European Union, with the manufacturing sector alone emitting 300 million tons of CO_2 in 2018, which is equivalent to one-fourth of Germany's total emissions (Rottner and Graevenitz, 2024). Through the EU ETS, the sector is also subject to stringent environmental regulations aimed at substantially decreasing emissions in the coming decade. At the same time, German firms are highly integrated into global supply chains, with more than 70% of firms sourcing intermediates from foreign countries. Together, these factors create ideal conditions for carbon leakage to occur.

I combine German administrative firm-level data on emissions, trade, and balance sheet information for the manufacturing sector between 2011 and 2018. I first provide direct reduced-form evidence for the carbon leakage mechanism by demonstrating that emissions and foreign inputs are substitutes. To estimate the effect of offshoring on emission intensity, I use exogenous variation in foreign prices caused by country-specific trade costs and productivity shocks. Consistent with other studies (Akerman et al., 2024; Dussaux et al., 2023; Leisner et al., 2022), offshoring, defined as the use of foreign inputs, reduces a firm's domestic emission intensity. If offshoring increases by 10%, a firm's emission intensity decreases by 0.26%. Moreover, the effect varies across firm-size bins, with larger firms reducing their emission intensity more. Differences in sourcing strategies can explain this variation, as large firms have access to a broader set of partner countries and, consequently, more imported varieties.

Next, I use the German data to document that differences in firms' sourcing strategies introduce significant variation in the import intensity and emission intensity of imported intermediate inputs across firms. Large firms use relatively more and more emission-intensive foreign intermediate inputs. This finding is explained by an extensive-margin effect. Larger firms source foreign intermediate inputs from more countries, including those with higher emission intensity of production, resulting in a higher emission intensity of their imports.

However, even though large firms use more and more emission-intensive foreign inputs, they also have a higher domestic emission intensity than that of their smaller counterparts. This finding contrasts with the literature (Barrows and Ollivier, 2018). Still, it can be explained by the composition of the German manufacturing sector, which has a high share of output from the most emission-intensive industries, which include steel, aluminum, cement, paper, and glass. Large firms operating in these industries benefit from several policies that grant access to cheap energy, making them relatively more emission-intensive.

Motivated by this empirical evidence from German firm-level data, I build a heterogeneous firm model to quantify the general equilibrium effects of climate policy changes. The model extends the firm-level input trade framework of Blaum et al. (2018) to include emissions as an additional input factor of production. Sourcing intermediate inputs is subject to fixed costs, but through love-of-variety and quality differences, foreign intermediate inputs reduce the production costs of a firm. Large firms import from more countries and have a higher import intensity. Independent of a firm's sourcing strategy, I assume that firms differ in their relative efficiency in using emissions. I call this emission-specific productivity the emission bias. This introduces variation in the emission intensity of firms.

My model differs from the standard environmental Melitz model with input trade in two dimensions. First, firm heterogeneity in import intensity and emission intensity introduces variation in firm exposure to climate policies. This gives rise to a reallocation of production output. Second, I depart from the standard assumption of a Cobb-Douglas production function, limiting the elasticity of substitution between different production factors to one. Peter and Ruane (2022) show that this restriction biases aggregate gains from trade liberalization.

To take the model to the data, I first estimate the elasticity of substitution between intermediate inputs and emissions. This elasticity is crucial for understanding carbon leakage because it indirectly influences the elasticity between domestic and foreign emissions. I follow Oberfield and Raval (2021) and estimate the elasticity using information on factor costs and a shift-share instrument based on international energy price variation. My findings indicate that emissions and inputs are substitutes, with the estimated elasticity ranging from 1.4 to 1.8, depending on the choice of weights for the shift-share instrument and the sample period.

Next, I estimate the parameters of the joint distributions of productivity, emission bias, and fixed costs of imports using a Simulated Method of Moments (SMM) approach. This method estimates the endogenous parameters of the joint distribution to minimize the distance between selected empirical and data moments. I use the observed firm-level distributions of value added, emissions intensity, and foreign shares as empirical counterparts for the productivity, emission bias, and fixed costs of importing. The estimated model matches all moments of the data. This stands in contrast with more aggregate versions of the model. Ignoring (i) heterogeneity in sourcing strategy, (ii) heterogeneity in emission bias, or (iii) heterogeneity in sourcing strategy and emission bias shows that introducing an emission bias is crucial not only to capture the correlation between firm size and emission intensity, but also to achieve the dispersion in emission intensity. Similarly, without fixed import costs, all firms would have the same foreign share. Hence, none of these aggregate models can fully capture all the features of the data. To further evaluate the ability of my model to fit the data, I estimate the effect of a 1% increase in the aggregate emission price by firm decile on emission intensity, output, offshoring, and the emission intensity of imports using (i) the German firm-level data and (ii) my calibrated baseline model. The predicted treatment effects of my baseline model match the estimated treatment effects of the data, even though my calibration did not target this result. Furthermore, this result sheds light on the heterogeneity in firms' responses to climate policy. Large firms decrease their emission intensity and increase their output, their imports, and their emission intensity of imports relative to smaller firms.

To quantify the emission and welfare effects of future increases in the domestic carbon price, I use the estimated model to simulate a counterfactual increase in domestic carbon prices for Germany, both with and without a carbon tariff. Specifically, I simulate an increase in the domestic carbon price from 10 to 100 €/t CO_2. My baseline model predicts an 11% decrease in emissions and welfare declines by €56 billion. The leakage rate is 25%: for every ton of domestic CO_2 saved, foreign emissions increase by 0.25 tons CO_2. More aggregate versions of the model predict a smaller decrease in emissions and a larger decrease in welfare. For emissions, their bias ranges between 2 and 20%, and for welfare, their bias is between 40 and 44%. The sign of the bias depends on whether the reallocation towards less emission-intensive firms or the offshoring of emissions is more prominent. This depends on the parametrization of the elasticities of substitution, the demand elasticity, and the joint distribution of parameters. In the calibrated version of my model, the reallocation channel dominates. Hence, the heterogeneous emission bias model has the smallest bias.

To better understand how a domestic carbon price increase affects leakage, I decompose leakage into four channels: changes in emission intensity, production, offshoring, and the emission intensity of imports. I find that global emission reductions are primarily driven by a decrease in the domestic emission intensity and output of firms and reallocation towards clean firms. This is partially offset by an increase in imports and, hence an increase in foreign emissions.

Next, I study the effectiveness of carbon tariffs in limiting carbon leakage. Carbon tariffs are one solution to mitigate carbon leakage without a globally coordinated policy (Farrokhi and Lashkaripour, 2025; Kortum and Weisbach, 2021). These tariffs impose a carbon price on the emissions embodied in imports, helping offset domestic cost disadvantages. The tariff corresponding to pricing emissions embodied in imports at the domestic carbon price is 8.5%. In the aggregate models, carbon tariffs reduce emissions by an additional 23 - 30%. In my baseline model, however, emissions increase because a carbon tariff reallocates production towards emission-intensive domestic firms with a low import intensity. In all models, welfare decreases substantially after the introduction of a carbon tariff. This additional reduction is largest in the baseline model, where the welfare loss more than doubles.

Literature Review This paper is related to several strands of the literature. First, it relates to the literature studying carbon leakage and carbon tariffs in the absence of a global carbon price. To mitigate leakage associated with the introduction of a domestic carbon price, governments can employ capacity-based subsidies (Meunier et al., 2014), output-based subsidies (Fowlie and Reguant, 2022), industry exemptions (Gerster and Lamp, 2024), or carbon border tariffs (Fischer and Fox, 2012; Fowlie et al., 2021). Even though most world trade is in intermediate goods, almost all studies focus on leakage in final goods. The exception is Artuc and Konstantin (2024), who introduce trade in intermediates in a multi-country model with perfectly competitive firms. I follow a different approach and focus on one country to highlight the role of firms in carbon leakage and welfare.

Second, the paper relates to the literature quantifying the environmental effects of offshoring, which can be split into empirical and theoretical contributions. Recent empirical studies using firm-level data have demonstrated that offshoring can lead to a reduction in the domestic emission intensity of firms (Akerman et al., 2024; Cole et al., 2021; Dussaux et al., 2023; Leisner et al., 2022; Li and Zhou, 2017).[1] Yet, the reason that emission intensity decreases is unclear, with evidence pointing to imports becoming more emission-intensive and productivity-enhancing effects. Complementary theoretical papers that study offshoring in the presence of environmental policy are Cherniwchan (2017), LaPlue and Erickson (2020), and Schenker et al. (2018). Closest to my research is Lim (2021), who studies the effect of offshoring on U.S. air pollution and calibrates her model using sectoral data. However, evidence on the role of firm heterogeneity is sparse, with several theoretical papers focusing only on heterogeneity in productivity (Chang et al., 2022; Graevenitz et al., 2024; Kreickemeier and Richter, 2014; Shapiro and Walker, 2018; Sogalla, 2023; Sogalla et al., 2024). I contribute to this literature by quantifying the general equilibrium effect of firm heterogeneity on carbon leakage and welfare. By using firm-level data, I can document the importance of reallocation across firms.

Third, an emerging literature focuses on the dispersion of heterogeneity in environmental performance across firms (Barrows and Ollivier, 2018; Leisner et al., 2022; Lyubich et al., 2018). While existing papers focus on the role of product, within-, and across-sector dispersion in emission intensity, I focus on the role of firm size and emission intensity. In contrast to the literature, I document a positive correlation between firm size and emission intensity when using value added as a measure of size. This is driven partially by the composition of the manufacturing sector in Germany and energy subsidies for large firms.

Methodologically, this paper relates to the literature modeling the importing behavior of heterogeneous firms (Blaum, 2024; Blaum et al., 2018; Gopinath and Neiman, 2014; Halpern et al., 2015; Ramanarayanan, 2020) and the role of firm heterogeneity for aggregate outcomes (Arkolakis et al., 2012; Blaum, 2024; Blaum et al., 2018; Brinatti and Morales, 2025). I extend Blaum et al. (2018) to incorporate firm heterogeneity in two input factors of production: intermediate inputs and

[1] Imbruno and Ketterer (2018) find the same holds for energy intensity in Indonesia.

emissions. Introducing firm heterogeneity in addition to productivity, leads to the reallocation of production across firms. I contribute to this literature by documenting the importance of firm heterogeneity for aggregate emissions, carbon leakage, and welfare when studying climate policies.

The rest of the paper is structured as follows: Section 1.2 contains a description of the data and empirical evidence, while Section 1.3 presents the theoretical model. Sections 1.4 and 1.5 contain the quantitative exercise and the counterfactual analysis. Section 1.6 concludes the paper.

1.2 Descriptive Evidence

In this section, I establish empirical evidence on (i) the effect of trade in intermediate inputs on domestic CO_2 emission intensity, (ii) firm heterogeneity in emission intensity, and (iii) differences in sourcing strategies across firms. I start with a description of the data and the construction of the variables, before presenting my results.

1.2.1 Data

German administrative data I use rich administrative data ("Amtliche Firmendaten für Deutschland") provided by the Federal Statistical Office of Germany from 2011 to 2019. For my analysis, I combine several data sources. The first dataset is the German manufacturing census at the firm level. Participation is mandatory for all establishments with more than 20 employees. The data include information on sales, employment, investment, and sectoral affiliation. Additional information on value added and expenditure on labor, energy, capital, and intermediate inputs are available for a sample of firms. I combine this information with plant-level data on energy consumption. Again, all plants with more than 20 employees must provide information on their energy consumption by energy type, electricity procurement, and electricity from self-generation. After aggregating the data to the firm level, I can construct CO_2 emissions at the firm level. Lastly, I use customs data, which provide information on quantity, value, and partner country for each firm's six-digit product-level imports and exports.
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Emission Intensity The dataset on energy consumption contains information on consumption for 14 different fuel types and electricity in kWh. Each fuel type and electricity can be matched to an annual emission factor provided by the German Environmental Agency (see Table A.21 in the Appendix for a list of energy types and emission factors). I calculate total CO_2 emissions for each firm by multiplying energy consumption by fuel type with its emission factor and summing up all energy types. Unless otherwise noted, I define emission intensity as emissions divided by the value added to measure the dirtiness of a firm's production. I use value added instead of sales to account for the emission offshoring effect of intermediate inputs.

Offshoring Measure I use several measures to measure a firm's offshoring activity. I follow Hummels et al. (2018) and define offshoring as imports that belong to the same industry as the firm. I distinguish between narrow offshoring (measure 1) and wide offshoring (measure 2). Narrow offshoring is offshoring within the firm's four-digit industry, while wide offshoring is offshoring within the firm's two-digit industry. As a third measure, I characterize all non-raw material imports (measure 3) as offshoring. Unless otherwise noted, the third measure of offshoring is used. Firms will use more foreign intermediate inputs solely because they are larger. However, to determine the leakage and welfare effect of the policy, the key measure of interest is a firm's relative import intensity. I define a firm's import intensity as the foreign share, which is the value of foreign intermediates divided by the sum of the value of domestic and foreign intermediates. Foreign intermediate inputs are the value of all non-raw material imports (measure 3).

Emission Intensity of Imports To measure the emissions embodied in a firm's imports, I need the emission intensities of foreign production. This information is available through environmentally extended multiregional input-output (EE MRIO) tables. Following the literature, I use EXIOBASE (Stadler et al., 2018).[2] EXIOBASE combines data from national accounts, energy accounts, and input-output tables, among other sources, to cover about 90% of global GDP. Data for 200 products across all sectors are available for 44 countries, plus five aggregate regions. The original dataset covers 1995-2011 but has been extended to 2022. EXIOBASE reports emissions from combustion and non-combustion activities. I convert emission intensity measures to 2015 Euros and merge them with HS6 trade flows. In cases where an exact match between EXIOBASE products and HS6 codes and products is impossible, I use an unweighted average over all matched products.

Final Data Sample For my analysis, I keep all firms that report information on their cost structure and positive sales. This reduces my sample to 134,123 observations. Although I drop more than 50% of the observations, more than 80% of emissions, production, and trade are covered, as summarized in Table 1.2. Due to the wave structure of the cost survey, which rotates smaller firms in and out of the survey every four years, the sample is not balanced. Table 1.1 presents summary statistics for the sample. There is considerable heterogeneity across firms in value added, emission intensity, and offshoring activity.

1.2.2 Stylized Facts

Fact 1 *Offshoring reduces domestic emission intensity but increases firms' emissions.*

A canonical trade-environment model assumes that as a firm's offshoring activity increases, its emission intensity decreases. The assumption is that emission offshoring - specifically the offshoring of dirty production stages and positive productivity effects of intermediates - leads to a decrease in emission intensity. To confirm that this relationship holds for Germany, I regress the emission intensity EI of a firm i in year t, defined as emissions from direct fuel and electricity consumption embodied in production divided by the value added or sales, on a variable measuring firm i's offshoring activity in year t, and a set of firm δ_i and year γ_t fixed effects:

$$\log(EI_{it}) = \beta_0 + \beta_1 \log(\text{Offshoring}_{it}) + \delta_i + \gamma_t + \epsilon_{it}. \tag{1.1}$$

Offshoring is defined here as all non-raw material imports and is instrumented using World Export Supply. Since my measures of international sourcing activity are not exogenous (e.g., there could be unobserved productivity shocks that reduce a firm's emissions intensity and increase its international sourcing), I follow the literature and construct a shift-share instrument following Hummels et al. (2014) using aggregate trade flows at the HS6 level from Comtrade. The instrument is constructed as follows:

[2] See Shapiro (2021) for a comparison of different EE MRIOs.

Table 1.1: Summary Statistics

	Mean	SD	p25	p50	p75	p90	p99
CO_2 emissions	19,106.43	315,016.78	207.42	721.50	3,123.52	12,176.97	205,980.66
Emission intensity	0.25	0.94	0.04	0.09	0.20	0.47	2.76
Employees	306.69	2,206.76	47.00	94.00	223.00	548.00	2,661.00
Export status	0.71	0.45	0.00	1.00	1.00	1.00	1.00
Foreign share	0.22	0.30	0.00	0.08	0.34	0.71	1.00
Implicit emission price	410.49	475.01	256.24	318.60	411.45	609.66	2,285.68
Import status	0.78	0.41	1.00	1.00	1.00	1.00	1.00
Number import partners	10.16	11.83	1.00	7.00	15.00	26.00	51.00
Offshoring (millions)	19.93	290.74	0.00	0.52	4.56	20.88	230.80
Sales (millions)	107.34	1,319.10	5.85	15.27	49.02	148.81	1,113.98
Sales per worker	242,077.59	548,654.56	104,213.17	160,160.77	255,715.56	426,078.19	144,0636.12
Value added (millions)	45.50	446.96	3.25	7.72	22.44	64.92	465.72

Notes: The table shows summary statistics for firms in the manufacturing sector from 2011-2018. The sample consists of 134,123 observations with 31,529 distinct firms. All nominal variables are expressed in Euros. CO_2 emissions are measured in tons. Emission intensity is measured in kg CO_2 per €value added. The implicit emission price is measured in €/t CO_2. For about 2% of the observations, no information on emissions is available. A firm is defined as an importer if it has a positive offshoring value. The number of import partners includes trade in raw material imports.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table 1.2: Representativeness of Data Sample

	Full data	Sample
CO_2 Emissions (thousand t)	324,816.58	298,930.19
Offshoring (millions)	292.99	266.76
Sales (millions)	1,798.23	1,537.54
Energy use (GWh)	1,071.11	997.33
Emission intensity (kWh/€)	0.18	0.19
Number firms	36,187	15,031

Notes: The table compares selected outcomes in 2014 for the full data, consisting of all firms with more than 20 employees, and a subsample of these data used in the analysis. CO_2 emissions, offshoring, sales, and energy use are the sum of all firms. Emission intensity is the average firm-emission intensity weighted by firm sales.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

$$WES_{it} = \sum_{ck} X_{ckt} s_{ick}^{pre}, \tag{1.2}$$

where X_{ckt} denotes aggregate exports of product k from country c in year t to all countries except Germany. s_{ick} is the import share of product k from country c for firm i in a pre-sample period. Intuitively, the instrument uses exogenous supply-side variation uncorrelated with firm-specific productivity shocks. The pre-sample year for all firms is 2011. Thus, for the instrument to be defined, a firm must continue to import a specific product from at least one country during the sample period. Borusyak et al. (2022)'s condition for consistency of the 2SLS estimator allows the variation in shares to be endogenous as long as the variation in shocks is exogenous. This requires shocks to be as good as randomly assigned and that firms are exposed to many small, independent shocks. Exposure shares in this setting can be viewed as endogenous, as (unobserved) differences in firm characteristics affect which products firms source from different countries. Variation in world exports of product k from country c may, for example, arise from country-specific productivity or trade cost shocks, which can be viewed as a quasi-experimental variation. Since firms on average import from nearly twelve different import partners, the exposure to each shock should be small enough and independent of the others.

I find that a 10% increase in offshoring reduces emissions intensity by 0.264%, all else being equal (see Table 1.3, column (2)), using value added as the denominator. The effect is slightly larger than the OLS estimate in column (1). I use the foreign share, defined as offshoring divided by total intermediate use, as an alternative measure. Here, the estimate of -0.0758 is statistically significant. To explore the role of firm heterogeneity, I add an interaction of the offshoring measure with firm size, measured by the number of employees (column (4)). Once I add the interaction term, the effect of offshoring becomes much smaller and insignificant. However, the effect of the interaction is statistically significant, negative, and economically relevant. The larger the firm, the more negative the effect of offshoring on emission intensity. Repeating the regression with emissions as the dependent variable shows that offshoring reduces firm

Table 1.3: Impact of Offshoring on Emission Intensity and Emissions

	Log Emission Intensity				Log Emissions
	(1)	(2)	(3)	(4)	(5)
Log Offshoring	-0.0211***	-0.0264**		-0.0145	-0.1044***
	(0.0021)	(0.0129)		(0.0173)	(0.0145)
Log Offshoring X Log Size				-0.0027*	0.0243***
				(0.0015)	(0.0013)
Foreign share			-0.0758***		
			(0.0128)		
First Stage					
Log WES		0.1057***		0.0047	0.0047
		(0.0069)		(0.0142)	(0.0142)
Log WES X Log Size				0.0181***	0.0181***
				(0.0023)	(0.0023)
F-Stat		236.87		87.22	87.22
Firm FE	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓
N	57,604	57,604	57,604	51,079	51,079

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. This table presents the results of regressing a firm's emission intensity on its offshoring activity, controlling for firm and year-fixed effects. Emission intensity is measured in kg CO_2/€in terms of value added, and the offshoring measure 3 is used. For the regression, the years 2012-2018 are used.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

emissions only for small firms (see column (5)), while large firms increase their emissions. These findings indicate that offshoring reduces firms' emission intensity. This reduction may occur directly through offshoring previously in-house, emission-intensive production stages or indirectly through productivity gains from substituting foreign intermediates for domestic ones. The idea is that offshoring can replace domestic intermediate inputs or domestic emissions. If imported intermediates replace mostly domestic intermediates, the effect on emission intensity will be smaller. The replacement of domestic with foreign intermediates is most likely happening during the sample period.[3]

In Table A.4, I show that the result is invariant to the choice of offshoring measure. For both narrow and wide offshoring, the estimates are more negative. Looking at the effect

[3]Compared to the literature (Akerman et al., 2024; Dussaux et al., 2023; Leisner et al., 2022), which finds an elasticity around 0.5, my elasticity is very small. Other studies include China's accession to the WTO and the EU's Eastern enlargement. A significant increase in trade in intermediate inputs with partner countries with high emission intensities characterizes both events.

heterogeneity across firm deciles, the largest firms experience a larger decrease in their emission intensity, but these results are not statistically significant.

Fact 2 *The relationship between firm size and emission intensity is nonlinear.*

To assess the general equilibrium effect of trade in intermediate inputs, it is crucial to know how firm size and emission intensity are correlated. It is commonly assumed that large, more productive firms use cleaner production technologies than small firms (Shapiro and Walker, 2018).

Figure 1.1 reveals a nonlinear relationship between firm size and emission intensity. At first, emission intensity decreases with size, but the sign reverses after reaching a threshold size. This finding also holds when using sales as a measure of firm size.

The composition of the German manufacturing sector drives the nonlinear relationship between firm size and emissions. Heterogeneity in emission intensity varies across two-digit industries: the most emission-intensive industries display a positive correlation between firm size and emission intensity. In contrast, in less emission-intensive industries, large firms are also less emission-intensive (Figure A.9). Since many large German firms produce in emission-intensive industries, such as chemicals, the correlation between firm size and emission intensity is, on average, positive.

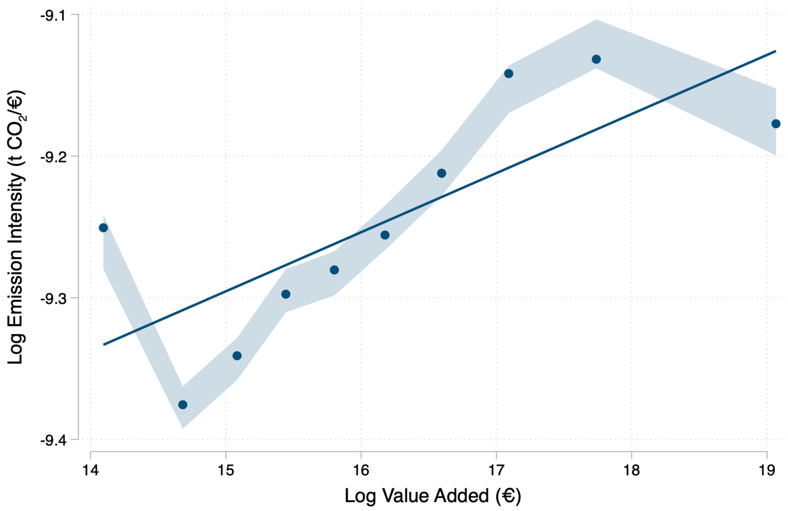
Several possible explanations exist for why large firms have a higher emission intensity. First, large firms are more likely to pay lower taxes on their energy consumption and emissions Gerster and Lamp (2024). Second, in Germany, large electricity consumers can buy electricity at a lower rate. Both conditions can result in large firms in emission-intensive industries facing a relatively lower emission price, making their production relatively more emission-intensive than that of small firms.

Fact 3 *Large firms rely more on emissions-intensive foreign intermediates.*

The amount of carbon leaked per firm depends on the amount of foreign intermediate inputs and their emission intensity. Both vary with firm size. Focusing on the importance of imported intermediates for firms of different sizes, Figure 1.2 shows that large firms use relatively more imports in their production. The foreign share, defined as offshoring expenditures divided by total intermediate expenditure, measures the relative importance of foreign intermediates. The foreign share increases with firm size. Heterogeneity across firms is pronounced. The largest firms spend almost four times as much on foreign intermediates as the smallest firms.

Variation in the foreign share can be driven by an extensive or an intensive-margin effect. Firms can increase their foreign share by starting to import from additional countries. Then different foreign shares can be explained by the extensive margin. Alternatively, all firms import from the same set of partner countries, but some firms import more from each country. Then, different foreign shares can be explained by the intensive-margin effect. Table 1.4 shows the foreign share, the share of importers, and the number of partner countries for different firm-size deciles. The foreign share is increasing with the share of importers and the number of partner countries. Small firms with a lower foreign share are less likely to be importers and import from relatively few partner countries compared with large firms. This evidence is consistent with an extensive-margin effect and, hence, a fixed cost to import from each additional country. If the intensive margin were the driver, then the share of importers and the number of partner countries would be more similar across deciles.

Figure 1.1: Emission Intensity and Firm Size



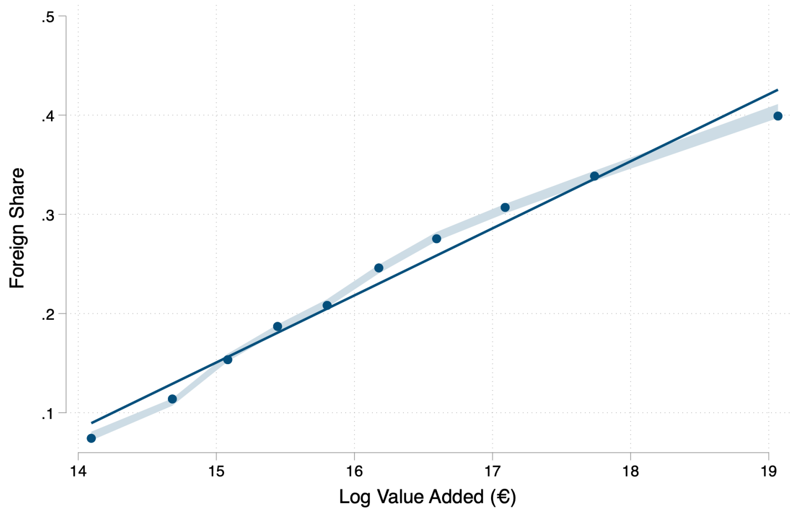
Notes: This figure shows a binscatter plot of log(emission intensity) as the dependent variable and log(value added) as the independent variable, controlling for four-digit industry and year fixed effects. Observations are divided into ten equally sized bins using the independent variable. For each bin, the mean of the independent variable and the mean of the dependent variable are calculated. Data for the dependent variable are residualized. Emission intensity is defined as tons of emissions divided by value added. The plot uses the years 2011-2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table 1.4: Extensive and Intensive Margin of Importing

VA Decile	1	2	3	4	5	6	7	8	9	10
Foreign share	0.11	0.13	0.18	0.22	0.24	0.28	0.30	0.28	0.31	0.42
Share importers	0.38	0.54	0.66	0.75	0.81	0.88	0.91	0.94	0.97	0.99
Import partners	1.48	2.59	3.72	5.12	6.60	8.83	11.37	14.04	19.11	30.12

Notes: This table reports the average foreign share, share of importing firms, and number of import partners by value added decile in 2014. Firms are divided into ten equally sized bins based on value added. The foreign share is defined as non–raw material imports divided by intermediate input expenditures. A firm is classified as an importer if it engages in offshoring.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure 1.2: Foreign Share and Firm Size



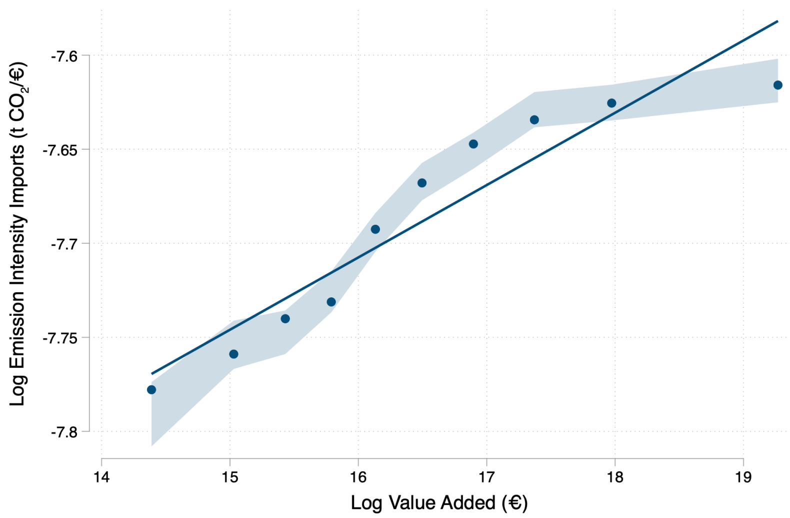
Notes: This figure shows a binscatter plot of foreign share as the dependent variable and log(value added) as the independent variable, controlling for four-digit industry and year fixed effects. Observations are divided into ten equally sized bins using the independent variable. For each bin, the mean of the independent variable and the mean of the dependent variable are computed. Data for the dependent variable are residualized. The foreign share is defined as imports excluding raw materials divided by expenditures on intermediate inputs. The plot uses the years 2011-2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Because sourcing locations differ across countries, the emission intensity of imports varies with firm size, as the emission intensity is dispersed at the country level. Large firms source from a different set of partner countries. In general, they have more trading partners and source from farther-away countries. These faraway countries are usually more emission-intensive in their production (see Figure A.1).

Figure 1.3 shows how the emission intensity of imports and firm size correlate. Large firms not only produce more emission-intensive products but also import more emission-intensive products. The effect seems to be at least partly driven by their sourcing strategy. Compared to the domestic emission intensity, the emission intensity of imports is less dispersed across firms. Lower implicit emission costs do not deter firms from importing emission-intensive intermediates. One possible explanation could be that the cost share of emissions is relatively low, while differences in labor or capital costs are the main determinants of a firm's sourcing strategy.

Summary This section presented facts highlighting the heterogeneity in emission intensity and sourcing strategy across firms. In Section 1.3, I build a model incorporating firm heterogeneity in sourcing strategy and emission intensity of production to quantify the effect of a changes in domestic carbon prices and a carbon tariff on carbon emissions and welfare.

Figure 1.3: Emission Intensity of Imports and Firm Size



Notes: This figure shows a binscatter plot of log(import emission intensity) as the dependent variable and log(value added) as the independent variable, controlling for four-digit industry and year. Observations are divided into ten equally sized bins using the independent variable. For each bin, the mean of the independent variable and the mean of the dependent variable are computed. Data for the dependent variable are residualized. The emission intensity of imports is defined as direct and indirect emissions divided by value added. The years 2011-2018 are used for the plot.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

1.3 Model

In this section, I introduce a quantitative model to study the role of firm heterogeneity on emission intensity in a globalized world. To achieve this, I extend the sourcing model by Blaum et al. (2018) to include emissions. The model features multiple sectors linked by input-output linkages, a firm-specific sourcing strategy that generates differences in the share of foreign inputs across firms, and firm differences in emission prices driven by technological choices.

1.3.1 Environment

Firms live in a small, open economy and produce differentiated varieties. The set of firms is fixed. A representative consumer is endowed with L units of labor. The supply of emissions is perfectly elastic, and one unit of emissions can be purchased at a price of p_E. Consumers allocate their income between a tradable manufacturing good and a non-tradable outside good.

Consumer preferences   I model the preferences of a representative agent as a two-tier utility function:

$$U = \prod_{s=1}^{S} C_s^{\alpha_s}. \tag{1.3}$$

The upper level is a Cobb-Douglas aggregator over sector aggregates. C_s denotes the industry aggregate of sector s, consisting of domestic varieties produced within the sector. There is one outside sector that is non-tradable. Expenditure shares $\alpha_s \in (0, 1)$, with $\sum_{s=1}^{S} \alpha_s = 1$, are constant and depend only on their price and income.

The lower-tier utility function is a CES composite of domestic varieties produced by firms within sector s, which are imperfect substitutes:

$$C_s = \left[\int_{\omega_s \in \Omega_s} q_s(\omega)^{\frac{\sigma_s - 1}{\sigma_s}} d\omega \right]^{\frac{\sigma_s}{\sigma_s - 1}}, \tag{1.4}$$

where $\sigma_s > 1$ represents the sector-specific elasticity of substitution and Ω_s is the set of produced varieties.

Production Each sector of the economy is populated by a set of heterogeneous firms denoted by Ω_s. Each firm produces a different variety indexed by ω_s. In the following, I replace ω with the index i. I treat the number of firms N_s within each sector as fixed. Competition is monopolistic. Firms employ four factors of production: capital K_i, labor L_i, emissions E_i, and intermediate inputs X_i, and produce their variety as follows:

$$q_i = \phi_i \left((1 - \beta_i) X_i^{\frac{\theta_s - 1}{\theta_s}} + \beta_i E_i^{\frac{\theta_s - 1}{\theta_s}} \right)^{\frac{\theta_s}{\theta_s - 1} \gamma_s} F(K, L)^{1 - \gamma_s}, \tag{1.5}$$

where ϕ_i represents productivity, θ_s is the sector-specific elasticity of substitution between intermediates and energy, β_i is the emission bias of a given firm, and γ_s is the material share of production. I restrict the production technology to a nested Cobb-Douglas-CES production function with nests driven by the allocation to primary and secondary production factors and the reduced-form evidence on the effect of offshoring on emission intensity. Nest one contains a labor-capital aggregate combined according to technology $F(\cdot)$, which I assume to be Cobb-Douglas. Nest two consists of the intermediate input bundle and emissions.

Firms can use domestic and foreign intermediate inputs X_{Fi}, which are imperfect substitutes:

$$X_i = \left[q_{Di} z_{Di}^{\frac{\epsilon_{Xs} - 1}{\epsilon_{Xs}}} + X_{Fi}^{\frac{\epsilon_{Xs} - 1}{\epsilon_{Xs}}} \right]^{\frac{\epsilon_{Xs}}{\epsilon_{Xs} - 1}}, \tag{1.6}$$

where q_{Di} and z_{Di} are the quantity and quality of the domestic input.

Sectoral linkages are modeled using a roundabout production structure (Caliendo and Parro, 2015), with each sector consuming a distinct input bundle composed of the output from all other sectors Y_j:

$$z_{Ds} = \prod_{j=1}^{S} Y_{js}^{\nu_{js}}, \tag{1.7}$$

where $\nu_{js} \in [0, 1]$ and $\sum_{j=1}^{S} \nu_{js} = 1$ specifies the sector-specific input-output linkages.

$$Y_{js} = \left(\int_0^{N_j} y_{vjs}^{\frac{\sigma_j - 1}{\sigma_j}} dv \right)^{\frac{\sigma_j}{\sigma_j - 1}} \tag{1.8}$$

Sourcing Strategy The foreign input bundle is a function of quality-adjusted q_c quantities z_c sourced from a firm-specific set of partner countries Σ_i, which is referred to as the sourcing strategy:

$$X_{Fi} = \left(\int_{c \in \Sigma_i} (q_c z_c)^{\frac{\kappa-1}{\kappa}} dG(q) \right)^{\frac{\kappa}{\kappa-1}}, \tag{1.9}$$

where c indicates the country from which inputs are imported and κ is the elasticity of substitution between inputs.

I further assume that firms face a firm-specific fixed cost f_i for importing inputs that are constant across countries. I also assume that the price of the input bundle is the same for all firms. Thus, the sourcing strategy is a function of quality. Then, the import price index is given by:

$$P_F(\Sigma_i) = \left(\int_{q \in \Sigma_i} p(q)/q^{1-\kappa} dG(q) \right)^{\frac{1}{1-\kappa}} = \left(\int_{q \in \Sigma_i} q^{\kappa-1} dG(q) \right)^{\frac{1}{1-\kappa}}. \tag{1.10}$$

I assume the country quality parameter follows a Pareto distribution characterized by shape parameter $\theta > 0$ and scale parameter q_m:

$$P_F(\Sigma_i) = \theta q_{\min}^{\theta} \left(\int_{q \in \Sigma_i} q^{\kappa-1} \theta^{-\theta-1} dG(q) \right)^{\frac{1}{1-\kappa}}. \tag{1.11}$$

Because of the assumption of constant fixed costs across countries, firms source from countries whose quality lies above a cut-off $\bar{q}_i$. Hence, the price index simplifies to:

$$P_{Fi}(n) = q_{i,min}^{-1} \left(\frac{\theta_s}{\theta_s - (\kappa - 1)} \right)^{\frac{1}{1-\kappa}} n^{\frac{-1}{\kappa-1}} = zn^{-\eta}, \tag{1.12}$$

where n is the mass of countries, firm i is sourcing from. z and n are functions of $(\kappa, \theta, q_{\min})$. Restricting $\theta > min[1, \kappa - 1]$, the price index P_F decreases in the number of partner countries.

Unit cost Using the CES properties of the production function, the unit cost of a given firm can be expressed as a function of parameters and prices.

$$u_i = \frac{1}{\phi_i} \left(\frac{w}{1-\gamma_s} \right)^{1-\gamma_s} \left(\frac{p_{Mi}}{\gamma_s} \right)^{\gamma_s} \tag{1.13}$$

with:

$$p_{Mi} = \left((1-\beta_i)^{\theta_s} Q(\Sigma_i)^{1-\theta_s} + \beta_i^{\theta_s} p_E^{1-\theta_s} \right)^{\frac{1}{1-\theta_s}}, \tag{1.14}$$

and

$$Q(\Sigma) = \left((p_D/q_D)^{1-\epsilon_{Xs}} + P_F(\Sigma)^{1-\epsilon_{Xs}} \right)^{\frac{1}{1-\epsilon_{Xs}}}, \tag{1.15}$$

where w is the price of the capital-labor bundle, p_E is the price of emissions consisting of the price of energy and a carbon tax t, p_M is the price index of materials, consisting of intermediate inputs and emissions, $Q(\Sigma_i)$ is the price index of intermediate inputs, p_D is the price of the domestic input bundle, and $P_F(\Sigma_i)$ is the price index of the foreign input bundle.

Standard calculations imply that the domestic share, defined as expenditure on domestic intermediate inputs divided by total intermediate input spending, is given by:

$$s_{Di} = \frac{(p_D/q_D)^{1-\epsilon_{Xs}}}{(p_D/q_D)^{1-\epsilon_{Xs}} + P_F(\Sigma)^{1-\epsilon_{Xs}}} = (p_D/q_D)^{1-\epsilon_{Xs}} Q(\Sigma_i)^{\epsilon_{Xs}-1}. \tag{1.16}$$

The foreign share is defined as:

$$s_{Fi} = 1 - s_{Di}. \tag{1.17}$$

Plugging in Equation 1.12, the domestic share can be expressed as a function of partner countries:

$$s_{Di}(n) = \left(1 + \left((p_D/q_D)\frac{1}{z}n^{\eta}\right)^{1-\epsilon_{Xs}}\right)^{-1}. \tag{1.18}$$

It follows that the unit cost can then be expressed as a function of the number of partner countries and the emission bias:

$$\begin{aligned} u_i(n) = {} & \frac{1}{\phi_i}\left(\frac{w}{1-\gamma_s}\right)^{1-\gamma_s}\left(\frac{1}{\gamma_s}\right)^{\gamma_s} \\ & \times \left((1-\beta_i)^{\theta_s} s_{Di}(n)^{\frac{1-\theta_s}{\epsilon_{Xs}-1}}\left(\frac{p_D}{q_D}\right)^{1-\theta_s} + \beta_i^{\theta_s} p_E^{1-\theta_s}\right)^{\frac{\gamma_s}{1-\theta_s}}. \end{aligned} \tag{1.19}$$

Pricing Decision and Profit Maximization Given their sourcing strategy and emission bias, firms choose their price to maximize their profits. Since consumer preferences are CES, the price equals a firm's unit cost u_i, multiplied by a constant markup:

$$p_i = \frac{\sigma_s}{\sigma_s - 1}u_i. \tag{1.20}$$

The consumer price index is then given by:

$$P_s = \left(\int p_i^{1-\sigma_s} di\right)^{\frac{1}{1-\sigma_s}}. \tag{1.21}$$

The profit maximization problem of a firm is given by:

$$\pi_i = \max_n \{u_i(n)^{(1-\sigma_s)}B - w(nf + f_I I(n > 0))\}, \tag{1.22}$$

where f denotes the country-specific fixed cost, and f_I is the fixed cost of importing. $B = \frac{1}{\sigma_s}\frac{\sigma_s}{\sigma_s-1}^{1-\sigma_s}P_s^{\sigma_s-1}S$ is defined as a function of the general equilibrium object P and S where S is aggregate spending. $u_i(n)$ is defined as above.

1.3.2 Changes in Trade and Environmental Policy

The following section presents theoretical results on how changes in the domestic emission price and carbon tariffs, specifically an increase in the price of the foreign intermediate good, affect emission intensity at the firm level in partial equilibrium. For tractability, I study firm responses in an economy with one sector and set w as the numéraire.

I show that an increase in the domestic emission price decreases the emission intensity of a firm, while a carbon tariff increases the emission intensity of a firm. Hence, if both instruments are combined, it is ex ante unclear whether the emission intensity of a firm and the aggregate emission intensity will increase or decrease. In the aggregate model without reallocation across firms, the aggregate and firm emission intensity coincide. Hence, the result can also be applied to the aggregate emission intensity. In models with additional firm heterogeneity, this conjecture does not hold. Differences in emission intensity and sourcing strategy introduce reallocation of production across firms, which will affect the aggregate emission intensity. Depending on the underlying distribution of these variables, the change in aggregate emission intensity is either upward or downward-biased.

Firm emission intensity Emission intensity is defined as a firm's emissions divided by value added. Using standard CES calculations, I get:

$$z_i = \left(\frac{\sigma_s - 1}{\sigma_s}\right)\left(\frac{\gamma_s}{1-\gamma_s}\right)\beta_i^{\theta_s} p_E^{-\theta_s}\left((1-\beta_i)^{\theta_s} Q(\Sigma_i)^{1-\theta_s} + \beta_i^{\theta_s} p_E^{1-\theta_s}\right)^{-1}. \tag{1.23}$$

Emission intensity, measured in terms of output value, does not directly depend on productivity. Productivity influences emission intensity indirectly through a firm's domestic share and emission bias, both of which are correlated with productivity.

Proposition 1: *An increase in the domestic emission price decreases emission intensity conditional on emissions and intermediate inputs being substitutes* $(1-\theta) < 0$.
Proof.

$$\begin{aligned}\frac{\partial z_i}{\partial p_E} &= \left(\frac{\sigma_s - 1}{\sigma_s}\right)\left(\frac{\gamma_s}{1-\gamma_s}\right) \\ &\quad \times \frac{-\theta_s \beta_i^{\theta_s}(1-\beta_i)^{\theta_s} Q(\Sigma_i)^{1-\theta_s} p_E^{-\theta_s - 1} - \beta_i^{2\theta_s}\left(\theta_s p_E^{-\theta_s} + (1-\theta_s) p_E^{-2\theta_s}\right)}{\left((1-\beta_i)^{\theta_s} Q(\Sigma_i)^{1-\theta_s} + \beta_i^{\theta_s} p_E^{1-\theta_s}\right)^2} < 0.\end{aligned} \tag{1.24}$$

If the government increases the emission price through a carbon tax increase, firms substitute other factors of production for emissions, leading to a cleaning up of domestic firms. These can be either labor or intermediate inputs. In the case of foreign intermediate inputs, however, this will come at the cost of relocating domestic emissions abroad.

In general, the response of a firm's emission intensity to an increase in the emission price depends on two components: the change in emissions and the change in value added. Suppose value added is more sensitive to a change in the emission price, e.g., a high demand elasticity σ_s. In that case, value added will decrease more, and the reduction in emission intensity will be stronger. This affects all firms in the same way. On the other hand, the change in emissions depends on the elasticity of substitution between emissions and intermediate inputs, in addition to the distribution of emission bias and fixed costs. Intuitively, large firms are hit harder by an increase in the emission price, but can compensate for this effect by having easier access to foreign intermediate inputs. Ex ante, it is unclear whether large, emission-intensive firms reduce their emission intensity more than small firms.

Proposition 2: *A carbon tariff increases domestic emission intensity conditional on emissions and intermediate inputs being substitutes* $(1-\theta)<0$.
Proof.

$$\begin{aligned}\frac{dz_i}{dP_{Fi}} =& -\left(\frac{\sigma_s-1}{\sigma_s}\right)\left(\frac{\gamma_s}{1-\gamma_s}\right)\beta_i^{\theta_s}p_E^{-\theta_s}\\ &\times\frac{(1-\beta_i)^{\theta_s}(1-\theta_s)Q(\Sigma_i)^{\frac{1}{1-\epsilon_{X_s}}-1-\theta_s}P_F^{-\epsilon_{X_s}}}{\left((1-\beta_i)^{\theta_s}Q(\Sigma_i)^{1-\theta_s}+\beta_i^{\theta_s}p_E^{1-\theta_s}\right)^2}>0.\end{aligned} \tag{1.25}$$

Hence, under a fairly general assumption that all production factors are substitutes, a carbon tariff increases the emission intensity of domestic firms as firms substitute away from foreign intermediates towards domestic inputs, including emissions. Conversely, trade liberalization, which corresponds to a decrease in the foreign price, reduces firm emission intensity through emission offshoring. This, however, will come at the cost of relocating domestic emissions abroad.

Similar to the reaction of emission intensity to the emission price, the magnitude of the change in emission intensity is not obvious. It depends on the relative change in value added and emissions. Additionally, the elasticity between foreign and domestic emissions becomes more important and determines how much emissions will change. Large firms using (relatively) more foreign intermediates are hit harder by a carbon tariff.

1.3.3 Carbon Leakage

Emission Intensity of Imports To compute carbon leakage, I need to take a stance on how the emission intensity of imports correlates with firm size. Larger firms source from more countries than smaller firms. Adding a country to a firm's sourcing strategy can either increase or decrease the emission intensity of imports. To express emission intensity as a function of the number of partner countries, I assume that the emission intensity of countries follows a Pareto distribution. Similar to the expression for the foreign price index, I derive the following equation:

$$EEI(n) = r_{min}^{-1}\left(\frac{\nu}{\nu-(\kappa-1)}\right)^{\frac{1}{1-\kappa}} n^{\frac{-1}{\kappa-1}} = vn^{-\iota}, \tag{1.26}$$

where n is the mass of countries from which the firm is sourcing. v and ι are functions of elasticity of substitution between foreign varieties κ and the shape ν and scale parameter r_{min} of the Pareto distribution.

Leakage Rate I use the leakage rate to measure carbon leakage, which is the amount of domestic emissions offset by an increase in emissions abroad. The leakage rate is defined by dividing the change in foreign emissions by the change in domestic emissions:

$$L = -\frac{\Delta\text{Foreign Emissions}}{\Delta\text{Domestic Emissions}}. \tag{1.27}$$

A leakage rate smaller than one implies that overall emissions decrease, while a leakage rate larger than one implies that overall emissions increase. The literature reports leakage rates between 10 to 40 % for final goods (Fowlie and Reguant, 2022; Sogalla, 2023) and 75 % for intermediate goods (Leisner et al., 2022).

Decomposition of Change in Global Emissions Building upon the leakage rate, I want to dissect the channels contributing to the change in domestic and foreign emissions and, hence, the leakage rate. I decompose the change in global emissions, the sum of domestic and foreign emission changes, into four parts:

$$\Delta E^{Global} = \underbrace{\underbrace{\int_i^{N_s} (z_i' - z_i) va_i \, di}_{\text{Emission substitution}} + \underbrace{\int_i^{N_s} (va_i' - va_i) z_i \, di}_{\text{Output}}}_{\Delta\text{Domestic emissions}} + \underbrace{\underbrace{\int_i^{N_s} (X_{Fi}' - X_{Fi}) z_i(X_{Fi}) \, di}_{\text{Offshoring}} + \underbrace{\int_i^{N_s} (z_i(X_{Fi})' - z_i(X_{Fi}))X_{Fi}) \, di}_{\text{Emission Intensity Imports}}}_{\Delta\text{Foreign emissions}}, \tag{1.28}$$

with (i) the change in domestic emissions due to emission substitution, (ii) the change in domestic output, the change in foreign emissions due to (iii) offshoring, and (iv) the emission intensity of imports. Domestic emissions can decrease either if firms become cleaner and reduce their emission intensity or through changes in firm output. Changes in output include the effect of output reduction and output reallocation towards more or less emission-intensive firms. Influenced by the changes in the input mix and output, firms' offshoring will also change. This happens through an extensive-margin effect. Firms add or drop countries from their sourcing set, which either increases or decreases their importing activity. As a by-product of this extensive-margin effect, the average emission intensity of imports will change as well if we assume that foreign countries differ in their emission intensity.

The contribution of the different channels depends on the underlying joint distribution of productivity, fixed costs of importing, and the emission bias, together with the parameters governing the elasticity of substitution between inputs and the demand elasticity.

1.3.4 Welfare

To account for the disutility of emissions for consumers, I follow Shapiro (2021) by modifying the utility function of the consumer as follows:

$$U = \prod_{s=1}^{S} C_s^{\alpha_s} f(E^{Global}) = \prod_{s=1}^{S} C_s^{\alpha_s} \left[1 + \delta\left(E^{Global} - E_0^{Global}\right)\right]. \tag{1.29}$$

Damages from global emissions, denoted by E^{Global}, enter utility in a multiplicative way through the function $f(\cdot)$, whose specification is chosen so that an increase in one ton of global emissions compared to a baseline emission level causes damages equal to the social cost of carbon. However, consumers ignore the effect of emissions on their utility, treating emissions as an externality.

After modifying the utility function to include environmental damages, the change in welfare can be decomposed into two components:

$$d\log W = \underbrace{d\log \frac{Y}{P}}_{\text{Real Income}} - \underbrace{d\log f(E^{Global})}_{\text{Disutility Emissions}} \tag{1.30}$$

The real income depends on the price index and nominal income, while nominal income is determined by labor income and the aggregate resource loss due to fixed costs. I assume income from emission prices and carbon taxes is lost to rent-seeking activities (Shapiro and Walker, 2018). The disutility of emissions increases with global emissions and the social cost of carbon.

1.3.5 Equilibrium

I assume that firms maximize profits and consumers maximize their utility, subject to their budget constraints. Moreover, the goods and labor markets clear, and trade is balanced. Additionally, I assume that the rest of the world (RoW) has the same CES demand structure as that of domestic consumers and firms. The supply of foreign intermediates and emissions is perfectly elastic. For more details, see Section A.3 in the Appendix.

1.4 Estimation of the Model

As shown in the previous sections, firm heterogeneity has implications for both domestic and global emissions. I calibrate a one-sector version of my model using German microdata to quantify the impact of emission subsidies and the increase in global trade of intermediate inputs. First, I estimate the key parameters of the model, followed by an outline of the calibration procedure. Finally, I present the calibration results and evaluate the model fit.

1.4.1 Estimation of Parameters

Elasticity of Demand   I use German microdata to compute the elasticity of substitution σ_s. I follow Oberfield and Raval (2021) and infer σ_s from firms' markups. Markups are defined as the ratio of total revenue to total costs. Following my model, I compute costs as the sum of wages, capital costs, and material expenditures:

$$\frac{revenue}{costs} = \frac{\sigma_s}{\sigma_s - 1}. \tag{1.31}$$

I obtain an average markup of 1.36, corresponding to an elasticity of substitution of 3.8. This value is on the higher end of the estimates featured in the literature.

Elasticity of Substitution for Intermediates and Emissions   Minimizing costs implies that, for a firm i, factor prices equal their marginal products. Using the first-order condition, it is possible to express the factor-cost ratio as a function of the elasticity of substitution and factor prices. See Raval (2019) for a more detailed derivation. Equation 1.32 identifies the elasticity of substitution between the intermediate input bundle and emissions using variation in the two-digit industry emission price $\bar{p}_{E,s}$:

$$log\left(\frac{p_X X_{is}}{p_E E_{is}}\right) = \beta_0 + \beta_1 log(\bar{p}_{E,s}) + \zeta_s G_{is} + e_{is}. \tag{1.32}$$

I construct $\bar{p}_{E,s}$ by taking a weighted average of the firm-specific emission prices. G_i includes controls for the four-digit industry, year, and a multi-plant dummy. $X_{i,s}$ is the quantity of intermediate inputs, while E_{is} is the quantity of emissions. The coefficient of interest is $\beta_1 = \eta - 1$.

Instruments I use differences in factor prices across two-digit industries to identify the elasticity of substitution. If these prices are correlated with unobserved industry characteristics such as market power or productivity, the OLS estimator of β will be biased. To address this endogeneity issue, I propose a version of the shift-share instrument by Hummels et al. (2014), which utilizes differences in the energy-input composition combined with foreign prices for energy. Variation in energy prices captures supply-side shocks independent of German firms' demand. Since Germany is a small, open economy, it does not have the power to influence market outcomes. I use pre-sample shares of energy inputs from 2011 to measure a firm's exposure to energy-supply shocks. I construct firm-level instruments for input prices and then take a weighted average to obtain industry-level instruments.

Hence, the instrument for the energy input price EIP_{it}^{E} at the firm level is defined as follows:

$$EIP_{it}^{E} = \Sigma_j s_{ikt_0} P_{jt}^{W}, \tag{1.33}$$

where j denotes the set of different energy inputs a given firm can use. s_{ijt_0} represents firm i's share of energy input j in year $t_0 = 2011$, while P_{jt}^{W} is an unweighted average of the price of energy input j, calculated using data from all countries except Germany in year t. I obtain data on energy input prices from the International Energy Agency (IEA).

Table 1.5: Elasticity of Substitution Between Emissions and Intermediates

	Log Input Cost Ratio			
	(1)	(2)	(3)	(4)
Log Average Emission Price	0.460***	0.486***	0.760***	0.815***
	(0.033)	(0.020)	(0.038)	(0.024)
Multi-plant Dummy	0.065***	0.041***	0.069***	0.056***
	(0.019)	(0.012)	(0.018)	(0.012)
First Stage				
Log EIP	0.111***	0.107***	0.113***	0.108***
	(0.006)	(0.006)	(0.003)	(0.004)
F-Stat	198.2	596.6	406.3	1203.0
Industry FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
N	42,116	90,887	42,124	90,898

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. This table presents the results of regressing a firm's intermediate input-energy factor-cost-ratio on its emission price, controlling for firm and year fixed effects. Columns (1) and (2) construct shares based on energy consumption, while columns (3) and (4) use emissions to construct shares. Columns (1) and (3) use the period 2012-2015, while columns (2) and (4) use the period 2012-2019.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table 1.5 shows the estimated elasticity of substitution between emissions and intermediate inputs. The estimates for this elasticity are between 1.5 and 1.8. Thus, both inputs can be classified as substitutes. For my calibration, I set the elasticity to 1.46.

Elasticity of Substitution for EII and Sourcing Strategy I need an estimate for the elasticity ι to calculate the emission intensity of imports and leaked emissions. Using Equation 1.26, the theory predicts a log-linear relationship between the number of sourcing locations n and the emission intensity of imports EEI, which can be estimated using German microdata and information on foreign emission intensities from Exiobase. I estimate the following regression:

$$\log(EII_i) = \delta_s + \delta_t + \phi \log(n_{ist}) + u_{ist}, \tag{1.34}$$

where n denotes the firm's average number of countries per product sourced. δ_s and δ_t are sector and year fixed effects. I measure products at the 6-digit level.

Table 1.6: Elasticity of Substitution Between Imported Emission Intensity and Imported Varieties

	Log Emission Intensity Imports				
	(1)	(2)	(3)	(4)	(5)
Log Number Varieties	0.146***	0.188***	0.189***	0.177***	0.089***
	(0.001)	(0.003)	(0.003)	(0.004)	(0.004)
Export Status			-0.020***	-0.001	0.006
			(0.005)	(0.008)	(0.008)
Log Capital/Worker				-0.009***	-0.008***
				(0.002)	(0.002)
Year FE	✓	✓	✓	✓	✓
Number Products		✓	✓	✓	✓
Industry FE	✓	✓	✓	✓	✓
N	219,903	219,816	219,816	102,706	91,958

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. The calculation of the emission intensity of imports is based on Exiobase. Column (5) considers only firms that import more than one variety.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

The results of the regression are displayed in Table 1.6. The emission intensity of imports increases with the number of imported varieties, measured by the number of foreign partner countries. Controlling for export status, the number of products, or the log capital-to-worker ratio changes the coefficient only slightly. However, restricting the sample to firms with more than one partner country nearly halves the coefficient. In my calibration, I use the smallest estimate of 0.089.

Other Parameters Table 1.7 provides an overview of the parameter estimates I use to calibrate my model. To identify γ, I divide material spending by the firm's total costs. For the carbon tax, I take the EU ETS price from 2014. ϵ_X and η are taken from Blaum et al. (2018).

Table 1.7: Calibrated Model Parameters

Description	Parameter	Estimate	Source
Demand elasticity	σ	4.10	German data
Output elasticity materials	γ	0.48	German data
EoS between emissions and intermediates	θ	1.46	German data
EoS between dom. and foreign intermediates	ϵ_X	2.38	Blaum et al. (2018)
Sensitivity P_F to mass sourcing countries	η	0.38	Blaum et al. (2018)
Sensitivity EII to mass sourcing countries	ι	0.09	German data
Price for one unit of emissions	t	10	EU ETS Price

Notes: This table reports the values of the calibrated parameters. The calibrated parameters are estimates using German firm-level data, aggregate data, or taken from the literature.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

1.4.2 Estimation Procedure

I allow for three dimensions of heterogeneity in my model: productivity ϕ_i, average fixed costs f_i, and emission bias β_i. I parameterize the distribution of the three parameters (ϕ_i, f_i, β_i) as a joint log-normal with means μ_ϕ, μ_f and μ_β, variances σ^2_ϕ, σ^2_f and σ^2_β and correlations $\rho_{f,\phi}$, $\rho_{\phi,\beta}$ and $\rho_{f,\beta}$.[4] I normalize average productivity to one. To solve the model, I use the simulated method of moments (SMM). The objective of the SMM is to minimize the distance between the data and model moments by picking values for the endogenous model parameters. Intuitively, the distribution of value added, the emission intensity, and the domestic share are the data equivalent of the distribution of ϕ_i, β_i, and f_i. Hence, the SMM estimates all parameters of (ϕ_i, f_i, β_i), the fixed costs of importing and the minimum emission intensity of imports. To estimate the parameters, I must match each model moment with a moment from the data. The model with full heterogeneity targets nine data and model moments. I use the dispersion in value added to identify the dispersion in productivity σ_ϕ. The aggregate emission intensity and the dispersion in firm emission intensity identify the mean and the dispersion of the emission bias β_i. The aggregate foreign share and the dispersion of the foreign share identify the mean and the dispersion of the firm-specific fixed costs to import from a country. The share of importing firms identifies the fixed costs of importing that all firms have to pay to start importing. The correlation between value added, emission intensity, and foreign share identifies the correlation between productivity, emission bias, and fixed costs. Lastly, I use the minimum emission intensity of imports to identify the average emission intensity of imports in the model.

[4] For consistency across the different models, I calibrate all models to feature variation along the intensive instead of the extensive margin. To do so, I introduce a home bias into the model to replace heterogeneity in fixed costs. See A.3.2 for details. As shown in Blaum et al. (2018), both approaches are nearly equivalent.

Table 1.8: Overview of Heterogeneity Models

	Aggregate	Het. Bias	Het. Sourcing	Baseline
Productivity	✓	✓	✓	✓
Emission bias	✗	✓	✗	✓
Fixed costs	✗	✗	✓	✓

Notes: This table introduces the naming convention for different versions of the model.

1.4.3 Model Fit

I calibrate four different versions of the model, differing in the degree of firm heterogeneity (see Table 1.8). First, the aggregate model features only heterogeneity in productivity, with all firms having the same foreign share and emission bias. Next, I allow firms to differ either in terms of their emission bias in the heterogeneous bias model, or in terms of their sourcing strategy in the heterogeneous sourcing model. Finally, in my baseline model, I incorporate both heterogeneous emission bias and heterogeneous sourcing strategy in addition to heterogeneous productivity.

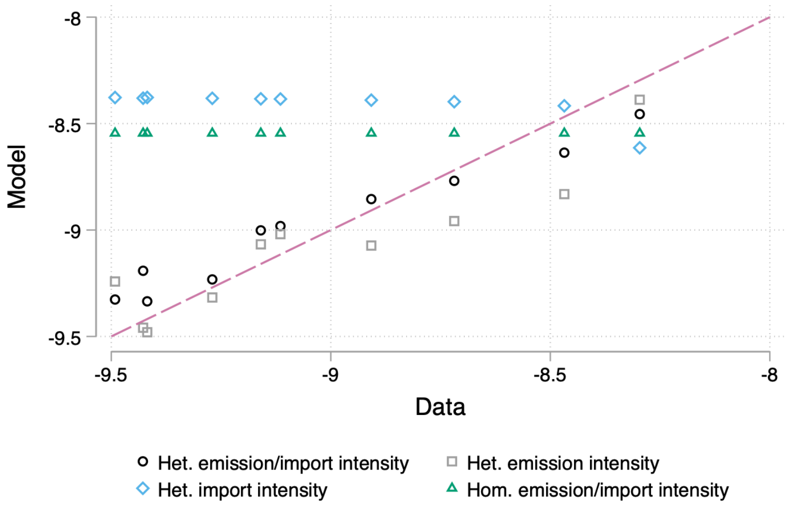
Table 1.9 shows the fit of the four different models. Overall, my baseline model fits the sign of all the targeted moments of the data. As expected, the heterogeneous bias model matches the distribution of emission intensity better than that of the foreign share. The heterogeneous sourcing model cannot fit the dispersion of emission intensity, which can be generated only through variation in sourcing strategies, and predicts a positive correlation between the domestic share and emission intensity. The aggregate model matches neither the distribution of emission intensity nor that of the foreign share. Table 1.10 displays the parameter estimates for the baseline model.

In Figure 1.4, I plot the distributions of the emission intensity and the foreign share for the data and all four versions of the model to verify that the model matches not only the moments, but also the distribution of the variables.

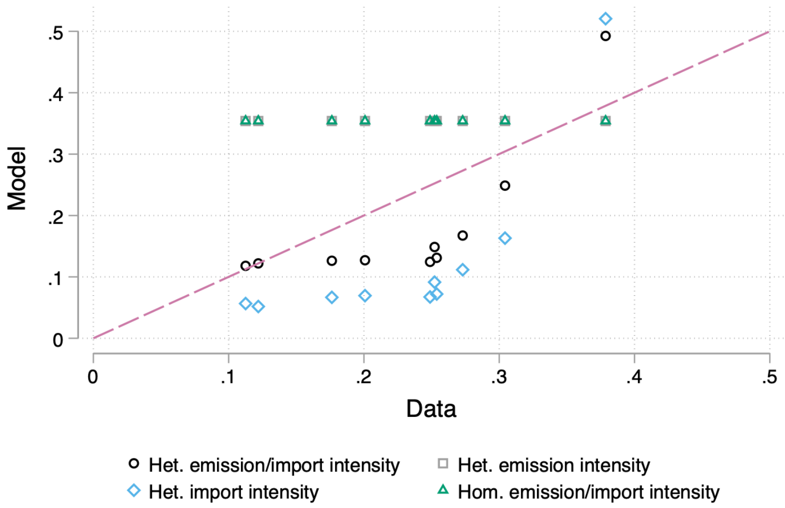
Figure 1.4a shows the distribution of the emission intensity for the four models and the data. Not surprisingly, the aggregate model does not feature any dispersion in emission intensity and cannot match the data. In the heterogeneous sourcing model, large firms have a lower emission intensity, caused by variation in the foreign share. Both models overpredict the emission intensity of small firms while underpredicting the emission intensity of large firms. The baseline and heterogeneous bias models match the distribution of log emission intensity well. Similar to the other models, they overpredict the emission intensity of small firms and underpredict the emission intensity of large firms, but to a lesser extent.

Figure 1.4b shows the distribution of the foreign share for the four models and the data. The aggregate and heterogeneous sourcing models do not feature any dispersion in the foreign share, and overpredict the foreign share for all but the largest firms. The baseline and heterogeneous sourcing models match the positive correlation between foreign share and firm size. However, they underpredict the foreign share for all but the largest firms and feature a jump in the foreign share for the largest firms.

Figure 1.4: Model Fit: Emission Intensity and Foreign Share



(a) Emission intensity



(b) Foreign share

Notes: This figure compares the model predictions to the data across four model versions. Panel (a) plots emission intensity by firm-size decile for both the data and the models. Panel (b) plots the foreign share by firm-size decile for the data and the models. Each point represents the average for a firm-size decile.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table 1.9: Model Moments

		Aggregate	Het. Bias	Het. Sourcing	Baseline
Moments	Data	Simulated			
Dispersion in log va	1.42	1.42	1.42	1.41	1.42
Agg. domestic share	0.65	0.65	0.65	0.64	0.64
Share of importers	0.78	1.00	1.00	0.78	0.78
Dispersion in log sD	0.51	0.00	0.00	0.51	0.50
Corr log va - log sD	-0.26	0.00	0.00	-0.25	-0.25
Agg. log z	-8.55	-8.55	-8.55	-8.54	-8.55
Dispersion in log z	1.27	0.00	1.27	0.01	1.27
Corr log va - log z	0.12	0.00	0.12	-0.25	0.11
Corr log sD - log z	-0.03	-1.00	0.00	0.98	-0.03
Agg. log EII	-7.07	-7.07	-7.07	-7.08	-7.07
Emission Ratio (D/F)	1.32	1.32	1.32	1.32	1.32

Notes: The table reports the data and model moments for the calibrated models using the SMM approach.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

1.5 Policy Experiment

Using the calibrated model, I want to study the effects of a change in the domestic carbon tax, both with and without a carbon tariff, on domestic and foreign emissions and welfare. The increase in the domestic emission price is calibrated to match a price increase from 10 to 100 €/t CO_2, simulating the rising prices of the EU ETS. The increase in the foreign price is calibrated to match a carbon tariff that applies the domestic carbon tax to emissions embodied in imports. I find that an increase in the domestic carbon price decreases emissions and welfare in all models. In general, a carbon tariff reduces emissions further unless the most import-intensive firms are more emission-intensive than foreign producers.

1.5.1 Domestic Carbon Price Increase

Context The European Union Emission Trading System (EU ETS) came into force in 2005 to reduce greenhouse gas emissions in the EU. While the social cost of carbon (SCC) is estimated to be at least €40, with estimates reaching over €400, the carbon price in the EU ETS remained below €35 until 2020.

To slow climate warming, the carbon price in the EU ETS will have to increase significantly in the future. The absence of a carbon tariff may have a detrimental effect on the domestic manufacturing sector due to the relocation of production. It may also lead to significant carbon leakage. To examine a moderate increase in carbon prices, I simulate a change in the carbon price to 100 €/t CO_2. Such a price increase has already been observed temporarily in 2023 and is also in line with projected carbon prices needed to meet EU emissions targets.

Table 1.10: Parameter Estimates for the Baseline Model

Parameter Description	Parameter	Estimate
Average home bias	μ_h	3.4773
Average emission bias	μ_β	5.9347
Dispersion emission bias	σ_β	1.0616
Correlation emission bias and efficiency	$\rho_{\phi,\beta}$	-0.1061
Fixed costs of importing	f_I	0.0001
Dispersion fixed costs	σ_f	1.6772
Correlation fixed costs and efficiency	$\rho_{f,\phi}$	0.2560
Correlation emission bias and fixed costs	$\rho_{\beta,f}$	0.1134
Minimum Emission Intensity of Imports	-	-9.3835
Emission price	p_E	1.3240

Notes: The table reports the parameter estimates for the baseline model using the SMM for calibration.

Results As shown in Table 1.11, all four models predict a decrease in emissions and feature carbon leakage. However, there are significant differences between the models. Aggregate models underestimate the emission reduction and either under- or overestimate leakage.

In the baseline model, domestic emissions would fall by 10.7% in response to the increase in the carbon price from 10 to 100 €/t CO_2. Consistent with the concept of emissions offshoring, foreign emissions increase by 8.1%. Global emissions, defined as the sum of domestic and foreign emissions, decrease by approximately 10.7% overall, which is significantly less than the reduction in domestic emissions. The leakage rate is 25% and similar to estimates for final good leakage rates from the literature, which range between 10 and 50%. However, it is smaller than the leakage rate for intermediate inputs of 75% found by Leisner et al. (2022) using reduced-form evidence.
In the three other, more aggregate models, global emissions decrease by between 8.5 - 10.5%. Hence, the bias of the aggregate models ranges between 2-20%, with the heterogeneous emission bias model being the closest. The bias is driven by different components. Models without heterogeneity in emission intensity underestimate the domestic emission reduction because they do not feature reallocation towards cleaner firms or, to a much smaller extent, in the heterogeneous sourcing model. Models without heterogeneity in sourcing strategy display lower emission offshoring because large firms increase their offshoring relative to smaller firms as they face lower costs to do so. Since these two effects bias the aggregate emission change in different directions, it is not clear whether the aggregate model would overestimate leakage relative to the baseline model, as the magnitude and direction of the bias depend closely on the parametrization of the model. Moreover, the biases for the global emission change and the leakage rate are not perfectly correlated. The baseline model has a higher leakage rate than the aggregate models without heterogeneity in sourcing strategy, but a lower leakage rate than the heterogeneous sourcing model. Again, the absence of heterogeneity in fixed costs biases the leakage rate downwards, whereas the heterogeneity in emission bias introduces reallocation in the baseline model, mitigating leakage.

Table 1.12 decomposes the absolute change in emissions in million tons into the four different channels of (i) emission intensity, (ii) output, (iii) offshoring, and (iv) the emission

Table 1.11: Effect of a Domestic Carbon Price Increase on Emissions

Model	Domestic (%)	Foreign (%)	Global (%)	Leakage Rate	Bias (%)
Baseline	-24.88	8.13	-10.68	0.25	0.00
Aggregate	-21.62	6.89	-9.35	0.24	-12.45
Het. sourcing	-22.16	9.55	-8.51	0.33	-20.29
Het. bias	-23.99	7.42	-10.48	0.23	-1.91

Notes: The table reports the percentage changes in domestic emissions (Col. 1), foreign emissions (Col. 2), global emissions (Col. 3), and the leakage rate (Col. 4) for a carbon price increase from 10 to 100 €/t CO_2. Column 5 shows the model bias in the change in global emissions relative to the baseline.

intensity of imports. In all models, the domestic emission reduction is driven by a change in the emission intensity of the firm. All firms produce less emission-intensively after the domestic carbon price increases. The reduction is stronger in the absence of emission intensity heterogeneity. This can be explained by the relatively stronger price increase in the domestic intermediate inputs bundle, limiting substitution towards intermediates. However, these two models feature a reduction in domestic emissions due to the output channel. The most emission-intensive firms shrink in absolute and relative terms. This effect is stronger than the increases in output of the clean firms and those with a low cost of sourcing. The increase in foreign emissions is driven by an increase in offshoring, with the composition of imports only marginally affecting total emissions. Overall, emissions go down by 56.06 million tons of CO_2 in the baseline model.

Table 1.12: Carbon Price Increase: Decomposition of the Change in Emissions

Model	Emission Intensity	Output	Offshoring	EI Imports	Total
Baseline	-63.59	-10.84	18.31	0.05	-56.06
Aggregate	-67.47	2.82	15.57	0.00	-49.08
Het. sourcing	-66.49	0.23	21.52	0.05	-44.69
Het. bias	-64.09	-7.67	16.76	0.00	-55.00

Notes: The table reports the decomposition of the change in global emissions into changes in emission intensity (Col. 1), output (Col. 2), offshoring (Col. 3), and the emission intensity of imports (col. 4) for a carbon price increase from 10 to 100 €/t CO_2. All values are in million t CO_2.

In addition to leakage, I want to explore the welfare effects of an increase in the carbon price. The welfare effect can be decomposed into two components: the change in consumers' real income and the change in emissions. On the one hand, the higher carbon price increases prices, resulting in a decline in real income. On the other hand, emissions decrease, which reduces the disutility associated with emissions as measured by the social cost of carbon. Ex ante, it is not clear which of these effects is stronger. I perform a back-of-the-envelope calculation to quantify the change in welfare in €, as shown in Table 1.13. For this calculation, I take values for the domestic emissions from the manufacturing sector, the emissions embodied in imports, the average wages in Germany, and the number of employees from the data. Additionally, I value each tonne of emissions at its social cost of carbon (SCC), which I assume to be equal to €150 (Rennert et al., 2022). The changes in emissions are taken from Table 1.11.

Table 1.13: Welfare Effects of a Carbon Price Increase

Model	Real Income (€)	Emissions (€)	Change Welfare (€)	Bias (%)
Baseline	-65.00	8.41	−56.59	0.00
Aggregate	-87.50	7.36	−80.14	41.62
Het. sourcing	-87.65	6.70	−80.94	43.04
Het. bias	-87.18	8.25	−78.93	39.49

Notes: The table reports the change in real income (Col. 1), disutility of emissions (Col. 2), and welfare (Col. 3) for a carbon price increase from 10 to 100 €/t CO_2. Units are in billion €. Column 4 shows the model bias in welfare relative to the baseline.

In the baseline model, an increase in the domestic carbon price to 100 €/t CO_2 results in an increase in the price by 2.63%, which is equivalent to a decrease of real income by €65.0 billion. Compared to the real income effect, consumers benefit moderately from the emissions reduction, amounting to about €9.06 billion. However, this benefit is insufficient to offset the loss in real income, resulting in a total welfare decline of €56 billion. This finding is consistent with the literature, which typically identifies the real income effect as being more significant than the emissions reduction effect (Shapiro, 2021; Shapiro, 2016). The other models overestimate the welfare losses by around 40% because they feature a larger increase in the price index, around 3.5%. In the baseline model, small firms cannot escape the carbon price shock. In the other models, they experience cost reductions through cheaper domestic or foreign intermediates. In the baseline model, however, domestic intermediates become more expensive, and offshoring is too costly.

1.5.2 Domestic Carbon Price Increase and Carbon Tariff

Context The second counterfactual examines how combining a domestic carbon price and a carbon tariff can prevent carbon leakage in the baseline model. Unlike domestic emissions subsidies, carbon tariffs, or a global carbon tax, aim to create a level playing field for all countries in terms of carbon prices without an equivalent carbon pricing mechanism abroad.

The carbon tariff prices emissions embodied in imports using the domestic carbon price. This is a simplified version of the Carbon Border Adjustment Mechanism (CBAM) proposed by the EU, abstracting from firm heterogeneity in the emission intensities of foreign countries.

Results Table 1.14 shows that a carbon tariff can limit carbon leakage and reduce global emissions compared to the scenario with only a domestic carbon price for all but the baseline model. Taxing emissions embodied in imports for each firm is equivalent to an average tariff of 6.75%, with firm-level tariffs ranging from 5.9% to 7.9%. Compared to the carbon price-only scenario, emissions increase by 7% in the baseline model and decrease by an additional 23-30% in the other models. These differences are driven by the different reactions to a carbon tariff. A carbon tariff, even on its own, increases emissions in the baseline model, whereas it decreases emissions in all other models. These reactions are shaped by the existence of emission-intensive firms with a low import intensity: emission-intensive firms with a low import intensity are growing as a response to a carbon tariff (see Figure 1.5a). Intuitively, the carbon tariff hurts firms with a high import intensity (see Figure 1.5d) most. All firms want to substitute away from foreign intermediates towards emissions, but the effect is strongest for import-intensive firms (see Figure 1.5c). This causes an increase in the domestic emission intensity (see Figure 1.5b). In the baseline model, high-emission-intensity and low-import-intensity firms exist. Conversely, they are the least affected, and production is reallocated towards them, and they increase offshoring by relatively less than other firms. Domestic emissions increase by more than in the aggregate models, and the offshoring response is less pronounced. In the baseline model, this effect can be strengthened by the fact that some of these emission-intensive and low import-intensity firms produce more emission-intensive than foreign producers.

The ranking of models in terms of emission reduction has changed. Now, the baseline model performs worst in terms of leakage rate and global emission reduction, whereas the heterogeneous bias models feature the largest emission reduction.

Table 1.14: Effect of a Domestic Carbon Price Increase and Carbon Tariff on Emissions

Model	Domestic (%)	Foreign (%)	Global (%)	Leakage Rate	Add. red. (%)
Baseline	-20.92	4.70	−9.90	0.17	−7.32
Aggregate	-20.85	−0.17	−11.96	−0.01	27.87
Het. sourcing	-20.85	1.84	−11.09	0.07	30.22
Het. bias	-22.75	0.22	−12.87	0.01	22.83

Notes: The table reports the percentage changes in domestic emissions (Col. 1), foreign emissions (Col. 2), global emissions (Col. 3), and the leakage rate (Col. 4) for a carbon price increase from 10 to 100 €/t CO_2 and a carbon tariff based on the emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. Column 5 shows the model bias in global emissions change relative to the baseline.

Table 1.15 decomposes the change in aggregate emissions into the four different channels. Compared to the carbon-tax-only scenario, the domestic emission intensity increases, and the reallocation channel in the models with heterogeneity in emission intensity is muted, especially in the baseline model. The carbon tariff distorts the efficient abatement of domestic emissions by reallocating production towards emission-intensive firms. Imported emissions decrease in all four models, but the carbon tariff is most effective at limiting imported emissions in models without heterogeneity in the import intensity. The change in the emission intensity of imports does not play an important role. Even though emissions in three out of four models

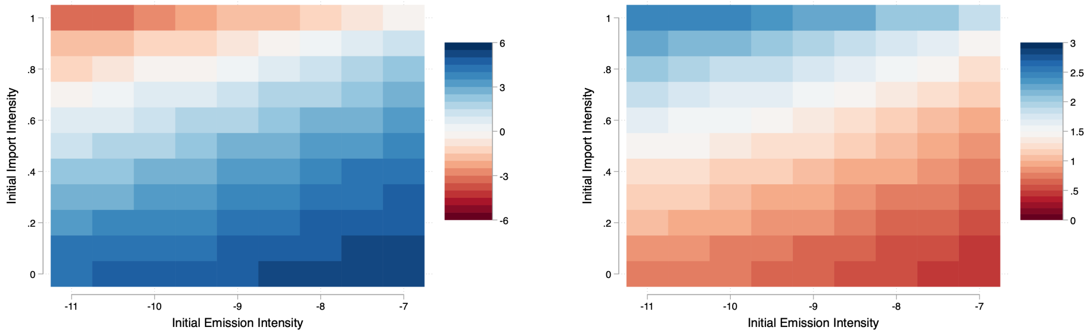
Table 1.15: Carbon Price Increase and Carbon Tariff: Decomposition of the Change in Emissions

Model	Emission Intensity	Output	Offshoring	EI Imports	Total
Baseline	-61.15	−1.42	10.66	−0.05	−51.96
Aggregate	-64.63	2.26	−0.39	0.00	−62.77
Het. sourcing	-64.51	2.15	4.20	−0.04	−58.20
Het. bias	-61.92	−6.13	0.50	0.00	−67.55

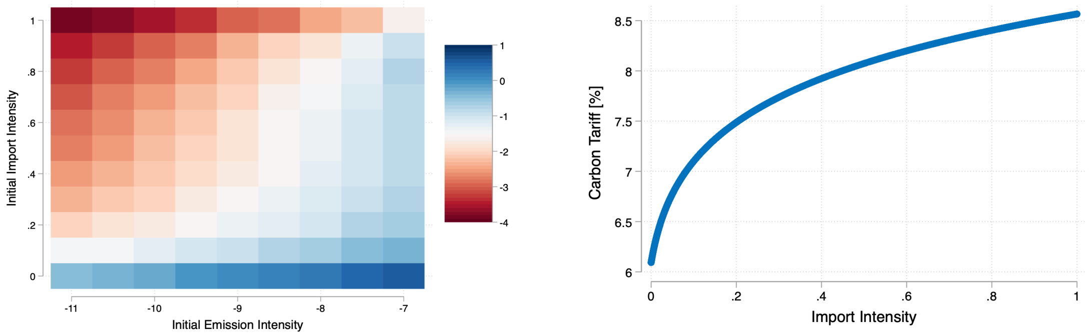
Notes: The table reports the decomposition of the change in global emissions into changes in emission intensity (Col. 1), output (Col. 2), offshoring (Col. 3), and the emission intensity of imports (Col. 4) for a carbon price increase from 10 to 100 €/t CO_2 and a carbon tariff based on the emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. All values are in million t CO_2.

decrease, welfare drops further in all four models. In the aggregate model, welfare decreases by an additional 36%. In the baseline model, welfare losses are more than double. Additionally,

Figure 1.5: Firm-level Effects of a Carbon Tariff



(a) Change in output (%) (b) Change in emission intensity (%)



(c) Change in imports (%) (d) Carbon tariff (%)

Notes: Panel (a) shows the change in output, Panel (b) shows the change in emission intensity, and Panel (c) shows the change in imports by firms' initial import and emission intensity due to the carbon tariff. Panel (d) shows the relationship between the carbon tariff and firms' import intensity.

welfare losses are the largest in models with heterogeneity in sourcing strategy. Large firms with a high import intensity and a low price are hit relatively harder, causing higher welfare losses in those models.

1.5.3 Sensitivity Analysis

In this section, I show that the change in emissions, the leakage rate, and the change in welfare are linear in the carbon price. Additionally, I show that even for high SCC estimates, consumer welfare decreases if the domestic carbon price increases. I simulate increases in the domestic carbon price for values between €10 and €500 per ton CO_2 for my baseline model.

Figure 1.6a shows emission reductions of a carbon tax with and without a carbon tariff for my baseline model. Emissions decrease nearly linearly in the carbon tax with and without a carbon tariff. However, the gap between the two scenarios widens as the carbon tax and marginal emission reductions become smaller. Although global emissions decrease with the carbon price, the leakage rate increases with the carbon price (see Figure 1.6b). A carbon tariff equivalent to the domestic carbon price reduces the leakage rate by a constant proportion below the leakage rate of the domestic carbon tax. However, the leakage rate remains well

Table 1.16: Welfare Effects of a Carbon Price Increase and Carbon Tariff

Model	Real Income (€)	Emissions (€)	Change Welfare (€)	Add. red. (%)
Baseline	-134.44	7.79	−126.64	123.79
Aggregate	-118.39	9.41	−108.97	35.98
Het. sourcing	-119.09	8.73	−110.36	36.34
Het. bias	-118.19	10.13	−108.05	36.89

Notes: The table reports the change in real income (Col. 1), disutility of emissions (Col. 2), and welfare (Col. 3) for a carbon price increase from 10 to 100 €/t CO_2 and a carbon tariff based on the emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. Units are in billion €. Column 4 shows the model bias in welfare relative to the baseline.

above zero for all except a carbon price of €14 per ton CO_2. To further decrease the leakage rate, the emissions embodied in imports would have to be taxed at a higher price than domestic emissions. Figure 1.6c and Figure 1.6d focus on the sensitivity of welfare losses with respect to the carbon price and the SCC. Similarly to the trend for emissions, welfare decreases with the carbon price. However, welfare reacts more sensitively to a carbon tariff than emissions do, and the gap between the two scenarios continues to grow with the carbon price. Besides the change in consumer income, the gap in welfare losses depends on the SCC. Contrary to changes in consumer income, measuring the SCC is less precise. The 95% confidence interval for the SCC is approximately between €40 and €400 per ton CO_2 (Rennert et al., 2022). Deviating from my standard assumption that the SCC is equal to €150 per ton CO_2 can hence change the welfare gap. For my preferred scenario of a carbon price increase to €100 per ton CO_2, welfare losses can be as small as €40 billion, which is approximately €15 billion less than my benchmark result.

1.5.4 Model Extensions

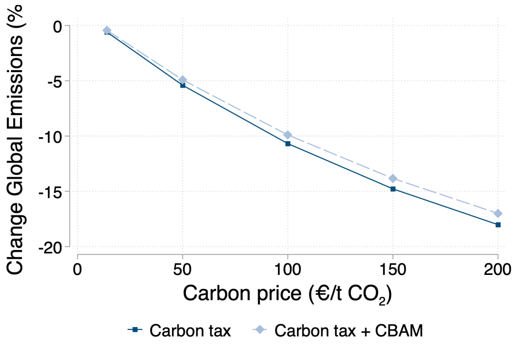
This section discusses possible extensions to the baseline model. To focus on the role of firm heterogeneity, the model focuses on a one-sector economy with input substitution towards intermediates and labor as the only available abatement mechanism. This abstracts from several other factors influencing leakage and welfare. In the following, I want to focus on the implementation of a domestic carbon tax for only selected industries, trade in final goods, an additional abatement channel through clean energy/technology, and the role of EU-wide cooperation in carbon taxation.

Multi-sector In my previous analysis, I assumed that all manufacturing firms must pay a carbon tax. However, only the most emission-intensive industries in Germany are covered by the EU ETS.[5] I plan to extend my model to a two-sector economy with input-output (IO) linkages to address this limitation. In this version, I classify firms into two sectors: dirty and clean. Only firms in the dirty sector are subject to a carbon price. This allows me to study the spillover effects of the carbon price on untreated firms and compare the emission reductions achieved when all firms are covered.

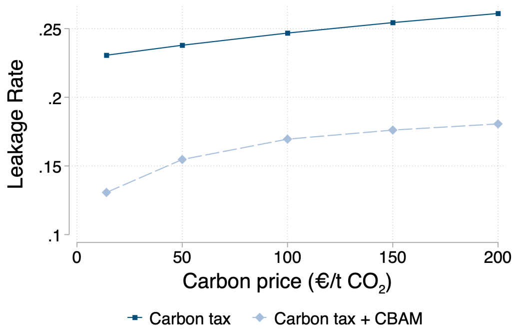
Figure A.9 and Figure A.10 in the Appendix show the heterogeneity in emission intensity, foreign share, and emission intensity between a clean and dirty industry. Here, I classify

[5] Industries vary widely in their emission intensity, as shown in Figure A.4a in the Appendix.

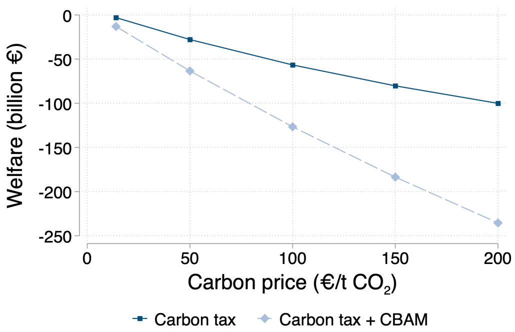
Figure 1.6: Alternative Carbon Prices and SCC



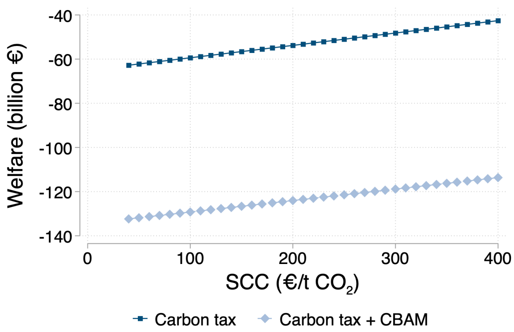
(a) Emissions for Different Carbon Prices



(b) Leakage for Different Carbon Prices



(c) Welfare for Different Carbon Prices



(d) Welfare for Different SCC

Notes: Panel (a) shows the change in global emissions, Panel (b) shows the change in the leakage rate, and Panel (c) shows the change in welfare for different carbon prices, with and without a carbon tariff. Panel (d) shows the sensitivity of the change in welfare to the social cost of carbon (SCC) for an increase in the carbon price from 10 to 100 €/t CO_2.

all 4-digit industries with an above-median emission intensity as dirty. My current model parametrization aligns with the characteristics of the dirty sector, where large firms are more emission-intensive. Including a clean sector in the analysis will increase leakage.

Trade in Final Goods Although this paper focuses on the role of firm heterogeneity in the leakage of intermediate inputs, leakage from final goods can occur simultaneously. When examining emissions embodied in imports (see Figure A.8 in the Appendix), it becomes evident that more emissions are imported via intermediate goods; however, the emissions from imported final goods are only slightly smaller in magnitude. By extending the model to include trade in final goods, I can distinguish between the contributions of different channels, which will help in designing effective policies.

Intuitively, leakage in final goods will replace the production of small firms with imported goods. Since small firms are, on average, cleaner and have lower leakage ratea, allowing for trade in final goods will increase leakage, assuming that imported goods are more emission-intensive than the production of small domestic firms.

Abatement and Clean Energy In my baseline model, the standard environmental trade abatement mechanism (Antweiler et al., 2001; Shapiro and Walker, 2018) is absent. This absence may lead to overestimating carbon leakage, as firms cannot abate emissions and can substitute only labor and intermediates to reduce their emissions. Hence, my estimates should be treated as an upper bound for leakage. To address this shortcoming, I plan to introduce two types of energy into my model: dirty and clean, which are imperfect substitutes for each other. All firms have access to dirty energy, which generates emissions. However, to access clean energy, firms must pay a fixed cost. In this context, I use renewable energy as a proxy for clean energy. Alternatively, one could consider including investment in clean production technology.

Figure A.12 in the Appendix shows the variation in the share of renewable energy across the firm size distribution.

EU Trade The EU is the most important import partner of German firms. Approximately 60% of the imported intermediates are from EU member countries. My model treats imports from EU ETS and non-EU ETS countries equally. However, this does not accurately reflect that countries covered by the EU ETS are likely to reduce their emission intensity. Moreover, they are subject to the CBAM. As a result, this may lead to an overestimation of leakage and underestimating firms switching to cleaner partner countries.

I plan to introduce a further distinction between EU and non-EU imports to overcome this shortcoming in my model. EU imports are cleaner and not subject to a carbon tariff, but their prices still rise. In contrast, non-EU imports are subject to a carbon tariff, yet the pass-through is incomplete. Furthermore, EU imports are assumed to become cleaner, while the emission intensity of non-EU imports remains the same. Although I do not include a multi-country version of the model in this analysis, these modifications allow me to obtain more precise estimates of carbon leakage.

1.6 Conclusion

This paper documents that German manufacturing firms exhibit varying emission intensities, even after controlling for input expenditures. Contrary to common assumptions, larger firms are characterized by higher emission intensity due to lower emission prices per unit. These lower emission prices result from differences in the underlying energy mix and firms' technologies to generate emissions. Moreover, firms differ in their shares of foreign intermediates and the emission intensities of imported intermediates. Building on these empirical facts, I propose a theoretical model with heterogeneous firms that differ in their import and emission intensities. I demonstrate that the model aligns with standard empirical results at the firm level.

In my quantitative exercise, I demonstrate that models lacking heterogeneity in sourcing strategy and emission bias fail to capture the characteristics of the German data. In a counterfactual analysis, I examine the effects of increasing the domestic carbon price from 10 to 100 €/t CO_2, with and without a carbon tariff. First, an aggregate model without firm heterogeneity would underestimate emission reductions and welfare losses. In my baseline model, an increase in the domestic carbon price from 10 to 100 €/t CO_2 reduces domestic emissions by about 25%, while foreign emissions increase by 8.1% without a carbon tariff. In contrast, the aggregate model predicts that domestic emissions decrease by only 2%, while foreign emissions increase by 7%. A carbon tariff can reduce leakage and lower global emissions in all but my baseline model.

Even though emissions fall in response to a carbon price increase, the welfare effects are negative because real income declines more than consumers benefit from the lower disutility associated with emissions. Moreover, accounting for the nonlinearity of carbon leakage in carbon prices is crucial if policymakers aim to minimize welfare losses.

The results should be viewed as an upper bound for welfare losses and a lower bound for emission reduction. My model features only input substitution as a way to reduce emissions. In reality, firms have the option to invest in abatement, switch to cleaner energy sources, or switch to cleaner import partners. Hence, the analysis can be extended along several dimensions. First, a multi-sector version could better capture the significant sectoral heterogeneity present in the data. Carbon leakage may be more or less pronounced depending on the sector, and consequently, the optimal policy might vary by industry. Second, this paper focuses solely on carbon leakage in intermediate inputs. An extended version of the model could consider carbon leakage in both final and intermediate inputs: a unilateral increase in carbon prices incentivizes emissions offshoring and exposes domestic firms to greater import competition. Third, switching to cleaner import partners or energy sources can be incorporated easily. Finally, given the varying importance of domestic and foreign emissions, carbon tariffs could be complemented by firm-specific domestic emission subsidies to achieve higher emission reductions.

Appendix to Chapter 1

A.1 Data Appendix

A.1.1 Data Cleaning

Data on energy use at the plant level is aggregated to the firm level and then combined with other datasets. While the German Statistical Agency employs several quality checks, resulting in generally good data quality, some inconsistencies persist, particularly in the reporting of energy use and materials. First, I eliminate all firms that report less than €1,000 in sales or have total energy use below 1,000 kWh. Second, due to misreporting, there are often significant fluctuations in reported values within firms over time. To address this, I impute any observations that differ by more than 30% from the values reported in periods t-1 and t+1, with the average of the adjoining periods. With data available starting in 1995, this adjustment does not affect my sample. Third, I impute missing observations for firms where data for the years t-1 and t+1 are available, using the average of the adjoining periods to ensure a balanced panel.

A.1.2 Trade Data Imputation

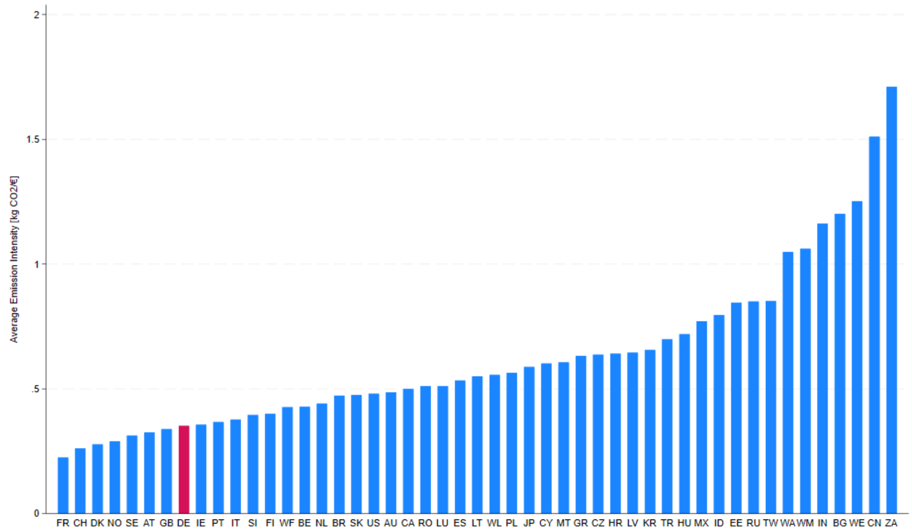
EU internal trade data for Germany are not collected at the firm level, but rather for tax groups ("Organkreise"). A tax group is an amalgamation of independent firms that jointly file taxes. Only the parent company reports the monthly trade flows within a tax group. The German Statistical Agency has implemented an algorithm based on information from the VAT information exchange system and product-level production data to allocate imports and exports to the integrated companies within a tax group. Kruse et al. (2021) provide more details on the implemented methodology and coverage of the data.

A.1.3 Emission Intensity of Foreign Production

My main source for foreign emission intensities is Exiobase. To calculate the emission intensity of imports, I focus on direct and indirect CO_2 emissions from fuel combustion. This variable is directly provided by Exiobase, but can also be calculated by multiplying the Leontief matrix with the factor production coefficient matrix S. Afterwards, I winsorize the data by industry and year to remove obvious outliers and convert the industry classification of Exiobase into HS codes, to merge the emission intensities with the German trade data. For countries without data, I assign the values of the regional aggregates. Missing observations are imputed with the country median. Figure A.1 depicts the Exiobase emission intensity of manufacturing for different countries using direct and indirect emissions. Germany, highlighted in red, is among the cleanest countries, similar to other European countries.

Exiobase's data quality is subject to criticism (Fowlie and Reguant, 2022). To exclude the possibility that my results are driven by false data, I conduct a robustness check using data on manufacturing emission intensities by country collected by the United Nations Sustainable

Figure A.1: Manufacturing Emission Intensity by Country



Notes: This figure shows the average emission intensity in kg CO_2 /€ in 2014 for countries in the Exiobase dataset. Emissions include direct and indirect emissions from fuel combustion.
Source: Stadler et al. (2018), own calculations.

Development Goals (UNSDG). However, compared to Exiobase, this includes only direct emissions.

A.2 Model Validation

To study the heterogeneity in firms' responses to climate policy and to validate the model, I compare the predicted treatment effects of my baseline model with the estimated treatment effects. In both cases, I study a 1% increase in the aggregate emission price. Building on the decomposition of global emissions change in Section 1.3.3, the focus is on output, emission intensity, offshoring, and the emission intensity of imports. Both my model and the data predict that large firms are more responsive to a carbon price shock. Large firms decrease their emission intensity and increase their output, their imports, and their emission intensity of imports relative to smaller firms.

A.2.1 Empirical Specification

For my model validation, I closely follow Brinatti and Morales (2025). Using the German firm-level data, I estimate the following regression:

$$\log(y_{i,t}) = \beta_0 + \beta_1 \log(pE^{Agg}_{s,t}) + \beta_2 \log(pE^{Agg}_{s,t}) \log(L_{i,t}) + \delta_i + \delta_s + \delta_t + \epsilon_{i,t}, \quad \text{(B.35)}$$

where $y_{i,t}$ is the output, emission intensity, offshoring, or emission intensity of imports for firm i in year t. $pE^{Agg}_{s,t}$ is the average implicit price of emissions firms pay in the two-digit industry s in year t. L is the size of firm i measured by employment. δ_i, δ_s, and δ_t are firm, industry and year fixed effects.

I construct an industry-level instrument for the emissions price, using variation in the energy-input composition combined with foreign energy prices to capture exogenous energy-supply shocks. To measure the exposure of an industry to energy supply shocks, I use pre-sample shares of energy inputs from 2011 for each industry. The instrument is defined as:

$$Z_{s,t} = \Sigma_j s_{j,s,t_0} P^W_{jt}, \quad \text{(B.36)}$$

where s_{j,s,t_0} is the share of energy input j in industry s in the pre-sample year t_0. P^W_{jt} is the average price of energy input j in all OECD countries excluding Germany. The validity of the instrument relies on the industries being exposed to small, independent, and random shocks. For example, variations in world market prices may arise from technology shocks or production shocks.

Results Table A.1 presents the average change in a firm's output (column 1), emission intensity (column 2), offshoring (column 3), and the emission intensity of imports (column 4) in response to an emission price shock. Panel A shows the OLS estimates, and Panel B shows the 2SLS estimates. The OLS and 2SLS estimates have the same signs, but the OLS estimates are downward-biased. The 2SLS estimates in column (1) suggest that, on average, firms increase their output measured by value added. The estimates in columns (2) and (3) show that firms simultaneously decrease their emission intensity and increase their use of imported intermediates. Column (4) suggests that firms use more imported intermediates and more emission-intensive imported intermediates. These estimates can be taken as evidence for emission offshoring, which, as a by-product, increases firm productivity. However, only the estimates for emission intensity and offshoring are statistically significant. My findings are similar to those of Fontagné and Schubert (2023), who studied energy shocks affecting French firms. They find that firms decrease their emission intensity and increase their imports of intermediate inputs. However, the effect on output is insignificant and close to zero for 2012 to 2019.[6]

Table A.1: Firm-level Effects of an Emission Price Increase

	Output	Emission Intensity	Offshoring	EII
	(1)	(2)	(3)	(4)
Panel A: OLS Estimates				
Log Industry Emission Price	0.0614	-0.1313	0.1657	0.0642
	(0.0530)	(0.0785)	(0.1459)	(0.0827)
Panel B: 2SLS Estimates				
Log Industry Emission Price	0.1692	-0.2484*	0.2880*	0.2550
	(0.1182)	(0.1330)	(0.1644)	(0.2363)
F-Stat	28.9	28.9	31.4	31.4
Firm FE	✓	✓	✓	✓
Industry FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
N	69,616	69,616	54,935	54,935

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. This table presents the results of regressing a firm's output, emission intensity, offshoring, and emission intensity of imports on the industry emission price; the industry emission price interacted with employment and year, industry, and firm fixed effects. Standard errors are clustered at the industry level.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

These average effects mask firm heterogeneity. In Table A.2, I present the estimates where I allow the effect to vary with firm size. Again, the OLS estimates in Panel A have the same sign as the 2SLS estimates in Panel B, but are downward biased. Starting with the estimate for output in column (1), I find a negative and statistically significant effect of the industry emission price on output. Still, the estimate for the interaction of the industry emission price with firm size is positive and statistically significant. The overall effect is positive for all firms with more than 16 employees. An increase in the industry emission price increases the output of all firms, but more so for large firms. Columns (2) to (4) show the estimates for emission intensity, offshoring, and the emission intensity of imports. While the estimates for the interaction term are highly statistically significant, the estimate for the industry emission price is not. Overall, the estimates suggest that firms decrease their emission intensity and increase their intermediate imports, as well as the emission intensity of their imports. The response of large firms is more pronounced for all three dependent variables.
Table A.3 shows the average firm response for different firm-size deciles. To compute the effect, I multiply the estimates by the average emission price and the average number of employees for each firm decile. Overall, the effects are relatively large. A 1% increase in the aggregate

[6] Colmer et al. (2025) study firms' responses to the EU ETS and find that regulated firms decrease their emission intensity, but find no significant effect on output and offshoring.

Table A.2: Effect Heterogeneity of an Emission Price Increase

	Output	Emission Intensity	Offshoring	EII
	(1)	(2)	(3)	(4)
Panel A: OLS Estimates				
Log Industry Emission Price	-0.2942***	-0.0665	-0.3860**	0.0315
	(0.0523)	(0.0835)	(0.1553)	(0.0816)
Log Industry Emission Price $\times$ Log L	0.0732***	-0.0133***	0.1106***	0.0066**
	(0.0042)	(0.0042)	(0.0135)	(0.0028)
Panel B: 2SLS Estimates				
Log Industry Emission Price	-0.2272*	-0.1517	-0.2758	0.2009
	(0.1303)	(0.1277)	(0.1742)	(0.2365)
Log Industry Emission Price $\times$ Log L	0.0834***	-0.0204***	0.1157***	0.0111**
	(0.0073)	(0.0062)	(0.0184)	(0.0047)
F-Stat	28.9	28.9	31.4	31.4
Firm FE	✓	✓	✓	✓
Industry FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
N	69,616	69,616	54,935	54,935

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Standard errors in parentheses. This table presents the results of regressing a firm's output, emission intensity, offshoring, and emission intensity of imports on the industry emission price; the industry emission price interacted with employment and year, industry, and firm fixed effects. Standard errors are clustered at the industry level.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

emission price decreases emission intensity by approximately 1.3% for the median firm. The change in imports of intermediates and output depends strongly on firm size. The largest firms increase their imports and output approximately four times more than the smallest firms. Overall, the effect for the median firm is smaller when accounting for firm heterogeneity. Without heterogeneity, firms would increase their output by 1.02%, while with heterogeneity, the median firm would increase its output by approximately 0.8%. Hence, aggregate estimates overestimate the median response.

A.2.2 Firm Response: Baseline Model and Data

Next, I want to compare the firm response predicted by the data and the model. I re-estimate Equation B.35 using the calibrated model and simulate a 1% increase in the aggregate emission price, which equals a carbon tax increase from €10 to €14. I compute the average response for each firm decile by multiplying the estimates by the aggregate emission price and the average employment for each firm decile.

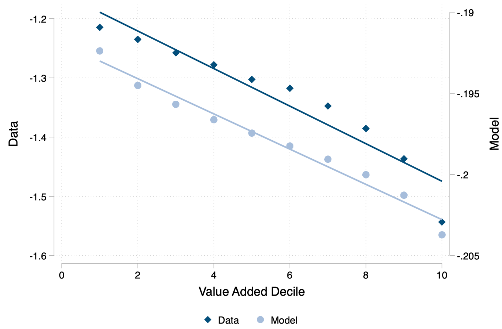
Table A.3: Firm Response to a 1% Emission Price Increase by Firm Decile

VA Decile	1	2	3	4	5	6	7	8	9	10
Output	0.33	0.43	0.54	0.64	0.75	0.85	0.99	1.15	1.39	1.84
Emission Intensity	-1.21	-1.23	-1.26	-1.28	-1.30	-1.32	-1.35	-1.39	-1.44	-1.54
Offshoring	0.67	0.81	0.96	1.10	1.25	1.39	1.58	1.80	2.13	2.77
EII	1.31	1.32	1.33	1.34	1.35	1.35	1.37	1.39	1.41	1.47

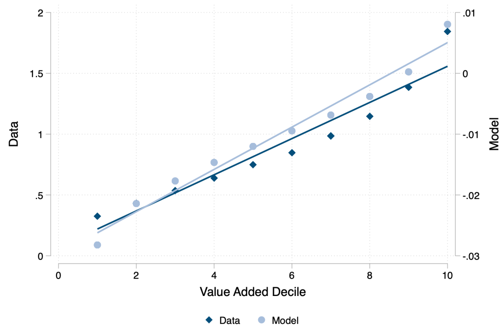
Notes: The table reports the mean % change for output, emission intensity, offshoring, and the emission intensity of imports in response to a 1% change in the aggregate emission price for different firm deciles. Firms are ranked based on their value added, with decile 1 being the firms with the lowest value added. The effects are computed using the estimates reported in Table A.2.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.2 compares the model response with the data. The model matches the predicted effects of the data well. Similar to the data, it predicts a decrease in emission intensity and an increase in output and offshoring. In the model, only the largest firms increase the emission intensity of imports. The model correctly predicts that large firms react more strongly to an increase in the emission price for all four outcome variables and matches the slope of the data response fairly well. Still, the effect size between the data and the model differs. However, this discrepancy in levels between the model and data estimates is expected, as the effects estimated using the German firm data cannot account for the general equilibrium effect on prices.

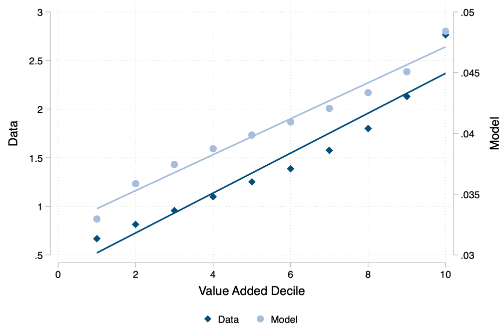
Figure A.2: Firm Responses: Baseline Model vs Data



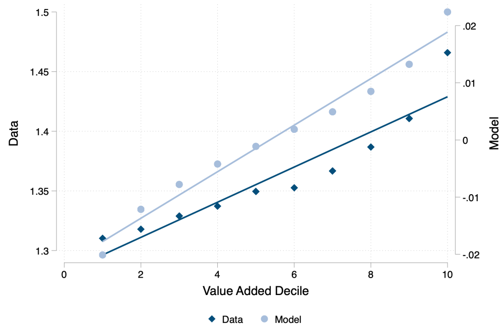
(a) Emission intensity



(b) Output



(c) Offshoring



(d) Emission Intensity of Imports

Notes: The figure shows the mean % change in (a) emission intensity, (b) output, (c) offshoring, and (d) the emission intensity of imports in response to a 1% change in the aggregate emission price for different firm deciles, comparing the data and the model. Firms are ranked based on their value added, with decile 1 being the firms with the lowest value added.

Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

A.3 Model Derivations

In the following, I provide the main derivations for a one-sector economy.

A.3.1 Firm Problem

Consumer preferences imply that firm revenue is given by:

$$R_i = p_i y_i = \left(\frac{p_i}{P}\right)^{1-\sigma} S, \tag{B.37}$$

where the price index P is defined as $P = \left(\int p_i^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}$ and S denotes total spending. Since firms charge a constant markup over unit costs, their price is equal to $p_i = \left(\frac{\sigma}{\sigma-1}\right) u_i$. Substituting this for the firm price, the expression can be written as:

$$p_i y_i = \left(\left(\frac{\sigma}{\sigma-1}\right) u_i P\right)^{\sigma-1} S. \tag{B.38}$$

Firms maximize profits by choosing the optimal domestic share sD:

$$\pi_i = \max_{sD_i \in [0,1]} \left\{ u(sD_i)^{(1-\sigma)} B - w(n(sD_i) f + f_I I(n > 0)) \right\} \tag{B.39}$$

with

$$\begin{aligned} u(sD) = & \left(\frac{1}{\phi_i}\left(\frac{w}{1-\gamma}\right)^{1-\gamma}\left(\frac{1}{\gamma}\right)^{\gamma}\right)^{1-\sigma} \\ & \times \left(\beta_i^\theta s_D(n)^{\frac{1-\theta}{\epsilon_X - 1}} \left(\frac{p_D}{q_D}\right)^{1-\theta} + (1-\beta_i)^\theta p_E^{1-\theta}\right)^{\frac{\gamma(1-\sigma)}{1-\theta}} \times B, \end{aligned} \tag{B.40}$$

$$B = \frac{1}{\sigma}\frac{\sigma}{\sigma-1}^{1-\sigma} P^{\sigma-1} S, \tag{B.41}$$

and

$$n(sD_i) = \left(\frac{1-sD_i}{sD_i}\right)^{\frac{1}{\eta(\epsilon-1)}} \left(\frac{zq_D}{p_D}^{\frac{1}{\eta}}\right). \tag{B.42}$$

The derivative of the profit function with respect to sD is given by:

$$\begin{aligned} \frac{\partial \pi_i}{\partial sD_i} = & \left(\frac{1}{\phi_i}\left(\frac{w}{1-\gamma}\right)^{1-\gamma}\left(\frac{1}{\gamma}\right)^{\gamma}\right)^{1-\sigma} B \frac{(1-\gamma)}{\epsilon - 1} \beta_i^\theta (p_D/q_D)^{1-\theta} \\ & \left(\beta_i^\theta s_D(n)^{\frac{1-\theta}{\epsilon_X - 1}} (p_D/q_D)^{1-\theta} + (1-\beta_i)^\theta p_E^{1-\theta}\right)^{\frac{\gamma(1-\sigma)}{1-\theta} - 1} \\ & - (1-sD_i)^{\frac{1-\eta(\epsilon-1)}{\eta(\epsilon-1)}} sD_i^{\frac{1-\theta}{\eta}} f = 0. \end{aligned} \tag{B.43}$$

A.3.2 Optimal Domestic Share of a Firm

For the calibration exercise, to achieve consistency across models, I assume that all firms are importers and that the fixed costs and fixed costs of importing are zero. To introduce variation in the domestic share, I assume that firms have a home bias α:

$$X_i = \left[\alpha_i q_D z_D^{\frac{\epsilon_X - 1}{\epsilon_X}} + (1-\alpha_i) X_F^{\frac{\epsilon_X - 1}{\epsilon_X}}\right]^{\frac{\epsilon_X}{\epsilon_X - 1}}. \tag{B.44}$$

With the home bias, the price index of intermediates is given by:

$$Q(\Sigma) = \left(\alpha_i^{\epsilon_X} (p_D/q_D)^{1-\epsilon_X} + (1-\alpha_i)^{\epsilon_X} P_F(\Sigma)^{1-\epsilon_X}\right)^{\frac{1}{1-\epsilon_X}}. \tag{B.45}$$

Solving for the domestic share and plugging in the import price index, we get that the domestic share is given by:

$$sD_i = \left(1 + \left(\frac{1-\alpha_i}{\alpha_i}\right)^{\epsilon_X} \left(\frac{p_D}{q_D z}\right)^{\epsilon_X - 1} n^{\eta(\epsilon_X - 1)}\right)^{-1}. \tag{B.46}$$

Setting $n = 1$, I can find the domestic share of a firm given its home bias α_i.

A.3.3 Import Status of a Firm

A firm imports if the net gains from importing are larger than zero, with the net gains being defined as the difference between profits if the firm is an importer π^I and profits if the firm is a non-importer π^D:

$$\pi^I - \pi^D > 0, \tag{B.47}$$

with π^I and π^D given by

$$\begin{aligned}\pi^I = &\left(\frac{1}{\phi_i}\left(\frac{w}{1-\gamma}\right)^{1-\gamma}\left(\frac{1}{\gamma}\right)^{\gamma}\left((1-\beta_i)^{\theta} s_D(n)^{\frac{1-\theta}{\epsilon_X - 1}} (p_D/q_D)^{1-\theta} + \beta_i^{\theta} p_E^{1-\theta}\right)^{\frac{\gamma}{1-\theta}}\right)^{1-\sigma} B \\ &- n(sD)f - f_I\end{aligned} \tag{B.48}$$

and

$$\pi^D = \left(\frac{1}{\phi_i}\left(\frac{w}{1-\gamma}\right)^{1-\gamma}\left(\frac{1}{\gamma}\right)^{\gamma}\left((1-\beta_i)^{\theta} (p_D/q_D)^{1-\theta} + \beta_i^{\theta} p_E^{1-\theta}\right)^{\frac{\gamma}{1-\theta}}\right)^{1-\sigma} B. \tag{B.49}$$

A.3.4 Emission Intensity

From the firm's cost minimization problem, it follows that the emissions of a firm are given by:

$$E_i = \frac{sE}{p_E}\frac{1}{\phi_i}\left(\frac{\gamma}{1-\gamma}\right)^{\gamma}\left(\frac{1}{pM_i}\right)^{1-\gamma} u_i^{-\sigma} P^{\sigma-1} S = \gamma\left(\frac{\sigma-1}{\sigma}\right)\frac{sE}{p_E}\left(\frac{p_i}{P}\right)^{1-\sigma} S, \tag{B.50}$$

where s_E is the emission share. s_E is defined by:

$$s_E = \frac{\beta_i^\theta p_E^{1-\theta}}{\beta_i^\theta p_E^{1-\theta} + (1-\beta_i)^\theta Q(\Sigma_i)^{1-\theta}} = \beta^\theta p_E^{1-\theta} p_M^{\theta-1}. \tag{B.51}$$

Dividing by value added $va = (1-\gamma)\left(\frac{p_i}{P}\right)^{1-\sigma} S$ gives us the emission intensity of firm i:

$$zi = \left(\frac{\sigma-1}{\sigma}\right)\frac{\gamma}{1-\gamma}\beta_i^\theta p_E^{-\theta}\left((1-\beta_i)^\theta Q(\Sigma)^{1-\theta} + \beta_i^\theta p_E^{1-\theta}\right)^{-1}. \tag{B.52}$$

A.3.5 General Equilibrium Variables

Total spending S consists of consumer income S^C, firms' expenditure for domestic intermediate inputs S^{DOM}, and exports S^{ROW}:

$$S = S^C + S^{DOM} + S^{ROW}. \tag{B.53}$$

Consumer income is the sum of labor income and profits. I assume that revenue from the carbon pricing scheme and carbon tariffs is lost due to rent-seeking:

$$S^C = \int l_i di + \frac{1}{\sigma} S. \tag{B.54}$$

Standard calculations for the Cobb-Douglas production function imply that the labor expenditure of a firm is:

$$l_i = \left(\frac{\sigma-1}{\sigma}\right)(1-\gamma)\left(\frac{p_i}{P}\right)^{1-\sigma} S. \tag{B.55}$$

Domestic intermediate expenditure and total import spending are given by:

$$\begin{aligned} S^{DOM} &= \int sX_i sD_i m_i di = \int sX_i sD_i \gamma s_i di \\ &= \int sX_i sD_i m_i \gamma \frac{\sigma-1}{\sigma} p_i y_i di \\ &= \gamma \frac{\sigma-1}{\sigma} S \int sX_i sD_i \left(\frac{p_i}{P}\right)^{1-\sigma} di \end{aligned} \tag{B.56}$$

and

$$\begin{aligned} S^{ROW} &= \int sX_i(1-sD_i) m_i di = \int sX_i(1-sD_i)\gamma s_i di \\ &= \int sX_i(1-sD_i) m_i \gamma \frac{\sigma-1}{\sigma} p_i y_i di \\ &= \gamma \frac{\sigma-1}{\sigma} S \int sX_i(1-sD_i)\left(\frac{p_i}{P}\right)^{1-\sigma} di. \end{aligned} \tag{B.57}$$

Combining these equations, total spending is given by:

$$
\begin{aligned}
S = &\left(\frac{\sigma-1}{\sigma}\right)(1-\gamma)S\int\left(\frac{p_i}{P}\right)^{1-\sigma}di + \frac{1}{\sigma}S \\
&+\gamma\frac{\sigma-1}{\sigma}S\left(\int sX_i\, sD_i\,\omega_i\,di + \int sX_i(1-sD_i)\,\omega_i\,di\right).
\end{aligned}
\tag{B.58}
$$

The price index, the second general equilibrium variable, can be expressed as:

$$
\begin{aligned}
P &= \frac{\sigma}{\sigma-1}\left(\int u_i^{1-\sigma}\,di\right)^{\frac{1}{1-\sigma}} \\
&= \frac{\sigma}{\sigma-1}\left(\int\left(\frac{1}{\phi_i}\left(\frac{w}{1-\gamma}\right)^{1-\gamma}\left(\frac{1}{\gamma}\right)^{\gamma}\right.\right. \\
&\quad\times\left.\left.\left(\beta_i^{\theta}\,s_D(n)^{\frac{1-\theta}{\epsilon_X-1}}\left(\frac{p_D}{q_D}\right)^{1-\theta}+(1-\beta_i)^{\theta}\,p_E^{1-\theta}\right)^{\frac{\gamma}{1-\theta}}\right)^{1-\sigma}di\right)^{\frac{1}{1-\sigma}}.
\end{aligned}
\tag{B.59}
$$

A.3.6 Equilibrium

The equilibrium is defined as a set of prices $[p_i]$ and allocations such that:

1. Firms maximize profits:

$$
\pi_i = \max_{sD}\big\{u(sD)^{(1-\sigma)}B - w(n(sD)f + f_I I(sD>0))\big\}.
\tag{B.60}
$$

2. Consumers maximize their utility, subject to their budget constraint:

$$
\int p_i c_i di = wL + \int \pi_i di.
\tag{B.61}
$$

3. Goods markets clear:

$$
y_i = c_i + y_i^{ROW} + \int y_v dv.
\tag{B.62}
$$

4. Labor markets clear:

$$
L = \int\big(l_i + l_i^F\big)di.
\tag{B.63}
$$

5. Trade is balanced:

$$
y_i^{ROW} = \int sD_i m_i di.
\tag{B.64}
$$

A.4 Calibration

A.4.1 Simulated Method of Moments Algorithm

As preparation, set the number of firms to 31,529 and draw shocks for productivity, fixed costs of sourcing, and emission bias from a standard normal for each firm.

1. Guess a value for each internal model parameter. Set the weighting matrix equal to the identity matrix.
2. Draw productivity, fixed costs of sourcing, and emission bias for given parameters and shocks.
3. Given parameters, find the fixed point where the general equilibrium objects S and P no longer change. For this, guess the initial S and P.
4. Given S and P, solve the model and compute each moment.
5. Compute Euclidean distance between data and model moments.
6. Iterate until the distance between data and model moments is small enough. Otherwise, go back to step 1.

A.5 Additional Tables

Table A.4: Impact of Narrow and Wide Offshoring on Emission intensity

	Log Emission Intensity	
	(1)	(2)
Log Offshoring (wide)	-0.0273	
	(0.0188)	
Log Offshoring (narrow)		-0.0234
		(0.0160)
First Stage		
log WES	0.0976***	0.1138***
	(0.0137)	(0.0163)
F-Statistics	50.5081	48.9238
Firm FE	✓	✓
Year FE	✓	✓
N	38,907	38,907

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. This table presents the results of regressing a firm's emission intensity on its offshoring activity, controlling for firm and year-fixed effects. For the regression, the years 2012-2018 are used.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table A.5: Correlation Between the Relative Domestic Share and Import Partners

	Log Relative Domestic Share				
	(1)	(2)	(3)	(4)	(5)
Log No. Varieties	1.535***	1.056***	1.055***	1.050***	0.998***
	(0.0071)	(0.0147)	(0.0148)	(0.0150)	(0.0160)
Export Status			0.018	0.023	0.212***
			(0.0281)	(0.0289)	(0.0326)
Log Capital/Worker				-0.015*	-0.003
				(0.0068)	(0.0069)
Year FE	✓	✓	✓	✓	✓
No. Products		✓	✓	✓	✓
Industry FE	✓	✓	✓	✓	✓
N	97,796	97,715	97,715	94,972	84,306

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. This table presents the results of regressing the relative domestic share of a firm, defined as the foreign share divided by the domestic share, on its number of imported varieties, export status, and capital per worker, while controlling for firm, product, and year fixed effects. For the regression, the years 2012-2018 are used.

Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table A.6: Exiobase: Correlation Firm Size and Emission Intensity Imports

	Log Emission Intensity Imports			
	(1)	(2)	(3)	(4)
Log Sales	0.0522***		0.0162***	
	(0.0001)		(0.0043)	
Log VA		0.0378***		0.0263***
		(0.0013)		(0.0063)
Year FE	✓	✓	✓	✓
Firm FE			✓	✓
Industry FE	✓	✓		
N	218,753	105,682	214,559	101,215

Notes:* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. The emission intensity of imports is calculated using Exiobase. *Source*: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table A.7: UNSDG: Correlation Firm Size and Emission Intensity Imports

	Log Emission Intensity Imports			
	(1)	(2)	(3)	(4)
Log Sales	0.0930***		0.0488***	
	(0.0013)		(0.0058)	
Log VA		0.0734***		0.0364***
		(0.0017)		(0.0080)
Year FE	✓	✓	✓	✓
Firm FE			✓	✓
Industry FE	✓	✓		
N	218,301	105,553	214,098	101,085

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust standard errors are in parentheses. The emission intensity of imports is calculated using UNSDG data. *Source*: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, UNSDG, own calculations.

Table A.8: Carbon Tariffs for Different Carbon Prices

	Carbon Price (€/t CO_2)					
	14	50	100	150	200	500
Panel A: Industry Carbon Tariff						
Aggregate, Het. emission bias	1.18	4.23	8.46	12.70	16.93	42.32
Het. Sourcing	1.18	4.23	8.46	12.69	16.92	42.29
Baseline	1.19	4.23	8.47	12.70	16.94	42.34
Panel B: CBAM Tariff						
Aggregate, Het. emission bias	1.18	4.23	8.46	12.70	16.93	42.32
Het. Sourcing	0.90	3.21	6.42	9.64	12.85	32.12
Baseline	0.95	3.38	6.75	10.13	13.51	33.77

Notes: This table reports the average carbon tariff (in %) for different domestic carbon prices. The industry carbon tariff is based on the aggregate emission intensity of imports, whereas the CBAM carbon tariff is based on the emission intensity of individual firms.

Table A.9: Effect on Emissions for Different Carbon Prices

	Change in Emissions (%)			
	Domestic (1)	Foreign (2)	Global (3)	Leakage Rate (4)
Panel A: Carbon price of 14 €/t CO_2				
Baseline	-1.36	0.42	-0.60	0.23
Aggregate	-1.18	0.34	-0.53	0.21
Het. sourcing	-1.21	0.46	-0.49	0.29
Het. emission bias	-1.33	0.36	-0.60	0.21
Panel B: Carbon price of 50 €/t CO_2				
Baseline	-12.44	3.92	-5.40	0.24
Aggregate	-10.77	3.22	-4.75	0.23
Het. sourcing	-11.05	4.43	-4.39	0.30
Het. emission bias	-12.05	3.47	-5.37	0.22
Panel C: Carbon price of 100 €/t CO_2				
Baseline	-24.88	8.13	-10.68	0.25
Aggregate	-21.62	6.89	-9.35	0.24
Het. sourcing	-22.16	9.55	-8.51	0.33
Het. emission bias	-23.99	7.42	-10.48	0.23
Panel D: Carbon price of 150 €/t CO_2				
Baseline	-34.78	11.72	-14.77	0.25
Aggregate	-30.32	10.23	-12.87	0.25
Het. sourcing	-31.05	14.24	-11.56	0.35
Het. emission bias	-33.43	11.01	-14.31	0.25
Panel E: Carbon price of 200 €/t CO_2				
Baseline	-42.78	14.79	-18.01	0.26
Aggregate	-37.44	13.29	-15.61	0.27
Het. sourcing	-38.31	18.59	-13.82	0.37
Het. emission bias	-41.05	14.29	-17.24	0.26
Panel F: Carbon price of 500 €/t CO_2				
Baseline	-69.58	26.44	-28.27	0.29
Aggregate	-62.36	27.60	-23.65	0.33
Het. sourcing	-63.54	39.32	-19.27	0.47
Het. emission bias	-66.70	29.53	-25.29	0.33

Notes: The table reports percentage changes in domestic emissions (Col. 1), foreign emissions (Col. 2), global emissions (Col. 3), and the leakage rate (Col. 4) for a carbon price increase from 10 to 14–500 €/t CO_2. Column 5 shows the model bias in global emissions change relative to the baseline.

Table A.10: Welfare Effects for Different Carbon Prices

	Real Income (1)	Emissions (2)	Welfare (3)
Panel A: Carbon price of 14 €/t CO_2			
Baseline	-3.49	0.47	-3.02
Aggregate	-4.47	0.42	-4.05
Het. sourcing	-4.50	0.39	-4.11
Het. emission bias	-4.47	0.47	-3.99
Panel B: Carbon price of 50 €/t CO_2			
Baseline	-32.10	4.25	-27.85
Aggregate	-42.04	3.74	-38.30
Het. sourcing	-42.23	3.46	-38.77
Het. emission bias	-41.96	4.23	-37.73
Panel C: Carbon price of 100 €/t CO_2			
Baseline	-65.00	8.41	-56.59
Aggregate	-87.50	7.36	-80.14
Het. sourcing	-87.65	6.70	-80.94
Het. emission bias	-87.18	8.25	-78.93
Panel D: Carbon price of 150 €/t CO_2			
Baseline	-91.89	11.63	-80.25
Aggregate	-126.79	10.14	-116.65
Het. sourcing	-126.67	9.10	-117.57
Het. emission bias	-126.10	11.27	-114.84
Panel E: Carbon price of 200 €/t CO_2			
Baseline	-114.26	14.19	-100.07
Aggregate	-161.19	12.30	-148.90
Het. sourcing	-160.65	10.89	-149.77
Het. emission bias	-160.06	13.57	-146.49
Panel F: Carbon price of 500 €/t CO_2			
Baseline	-195.79	22.26	-173.53
Aggregate	-304.53	18.62	-285.91
Het. sourcing	-300.25	15.17	-285.07
Het. emission bias	-300.33	19.92	-280.42

Notes: The table reports the change in real income (Col. 1), disutility of emissions (Col. 2), and welfare (Col. 3) for a carbon price increase from 10 to 15-500 €/t CO_2. Column 4 shows the model bias in welfare relative to the baseline. All values are in billion €.

Table A.11: Decomposition for Different Carbon Prices

	EI (1)	Output (2)	Imports (3)	EII (4)	Total (5)
Panel A: Carbon price of 14 €/t CO_2					
Baseline	-3.46	-0.62	0.94	0.00	-3.14
Aggregate	-3.70	0.18	0.76	0.00	-2.77
Het. sourcing	-3.64	0.02	1.03	0.00	-2.59
Het. emission bias	-3.49	-0.48	0.82	0.00	-3.16
Panel B: Carbon price of 50 €/t CO_2					
Baseline	-31.65	-6.17	8.82	0.03	-28.35
Aggregate	-33.74	1.71	7.28	0.00	-24.95
Het. sourcing	-33.21	0.20	10.00	0.02	-23.04
Het. emission bias	-31.92	-4.59	7.84	0.00	-28.20
Panel C: Carbon price of 100 €/t CO_2					
Baseline	-63.59	-13.60	18.31	0.05	-56.06
Aggregate	-67.47	3.64	15.57	0.00	-49.08
Het. sourcing	-66.49	0.39	21.52	0.05	-44.69
Het. emission bias	-64.09	-9.69	16.76	0.00	-55.00
Panel D: Carbon price of 150 €/t CO_2					
Baseline	-89.29	-20.65	26.38	0.08	-77.56
Aggregate	-94.38	5.39	23.11	0.00	-67.58
Het. sourcing	-93.08	0.53	32.11	0.07	-60.67
Het. emission bias	-89.93	-14.21	24.87	0.00	-75.12
Panel E: Carbon price of 200 €/t CO_2					
Baseline	-110.38	-27.30	33.30	0.10	-94.57
Aggregate	-116.27	6.99	30.03	0.00	-81.97
Het. sourcing	-114.75	0.63	41.91	0.08	-72.57
Het. emission bias	-111.11	-18.27	32.28	0.00	-90.49
Panel F: Carbon price of 500 €/t CO_2					
Baseline	-184.52	-59.47	59.52	0.17	-148.42
Aggregate	-191.66	14.33	62.35	0.00	-124.16
Het. sourcing	-189.78	0.82	88.64	0.16	-101.16
Het. emission bias	-185.36	-36.10	66.71	0.00	-132.79

Notes: The table reports the decomposition of the change in global emissions into changes in emission intensity (Col. 1), output (Col. 2), offshoring (Col. 3), and the emission intensity of imports (Col. 4) for a carbon price increase from 10 to 14-100 €/t CO_2. All values are in million t CO_2.

Table A.12: Effect on Emissions for Different Import Prices

	Change in Emissions (%)			
	Domestic (1)	Foreign (2)	Global (3)	Leakage Rate (4)
Panel A: Carbon price of 14 €/t CO_2				
Baseline	0.68	-0.54	0.15	0.60
Aggregate	0.13	-1.00	-0.35	5.60
Het. sourcing	0.23	-1.07	-0.33	3.57
Het. emission bias	0.23	-1.01	-0.31	3.36
Panel B: Carbon price of 50 €/t CO_2				
Baseline	2.39	-1.92	0.54	0.61
Aggregate	0.47	-3.49	-1.23	5.62
Het. sourcing	0.79	-3.72	-1.16	3.58
Het. emission bias	0.80	-3.54	-1.07	3.37
Panel C: Carbon price of 100 €/t CO_2				
Baseline	4.69	-3.79	1.04	0.61
Aggregate	0.91	-6.78	-2.40	5.64
Het. sourcing	1.52	-7.21	-2.24	3.58
Het. emission bias	1.54	-6.88	-2.08	3.37
Panel D: Carbon price of 150 €/t CO_2				
Baseline	6.89	-5.62	1.51	0.62
Aggregate	1.32	-9.88	-3.50	5.66
Het. sourcing	2.21	-10.48	-3.25	3.59
Het. emission bias	2.24	-10.03	-3.04	3.37
Panel E: Carbon price of 200 €/t CO_2				
Baseline	9.01	-7.39	1.96	0.62
Aggregate	1.70	-12.82	-4.54	5.68
Het. sourcing	2.85	-13.56	-4.21	3.59
Het. emission bias	2.91	-13.00	-3.94	3.38
Panel F: Carbon price of 500 €/t CO_2				
Baseline	20.13	-17.07	4.13	0.64
Aggregate	3.59	-27.51	-9.79	5.79
Het. sourcing	5.97	-28.65	-8.93	3.62
Het. emission bias	6.18	-27.85	-8.46	3.40

Notes: The table reports percentage changes in domestic emissions (Col. 1), foreign emissions (Col. 2), global emissions (Col. 3), and the leakage rate (Col. 4) for a carbon tariff based on the emission intensity of firm imports. The carbon tariff applies the domestic carbon price, ranging from 14 to 500 €/t CO_2. Column 5 shows the model bias in global emissions change relative to the baseline.

Table A.13: Welfare Effects for Different Import Prices

	Real Income (1)	Emissions (2)	Welfare (3)
Panel A: Carbon price of 14 €/t CO_2			
Baseline	-9.81	-0.12	-9.93
Aggregate	-4.52	0.28	-4.24
Het. sourcing	-4.52	0.26	-4.26
Het. emission bias	-4.52	0.24	-4.28
Panel B: Carbon price of 50 €/t CO_2			
Baseline	-34.17	-0.42	-34.59
Aggregate	-15.69	0.97	-14.72
Het. sourcing	-15.68	0.91	-14.77
Het. emission bias	-15.69	0.84	-14.84
Panel C: Carbon price of 100 €/t CO_2			
Baseline	-66.04	-0.82	-66.86
Aggregate	-30.22	1.89	-28.33
Het. sourcing	-30.17	1.76	-28.41
Het. emission bias	-30.21	1.64	-28.57
Panel D: Carbon price of 150 €/t CO_2			
Baseline	-95.83	-1.19	-97.02
Aggregate	-43.72	2.76	-40.96
Het. sourcing	-43.61	2.56	-41.04
Het. emission bias	-43.69	2.39	-41.30
Panel E: Carbon price of 200 €/t CO_2			
Baseline	-123.75	-1.54	-125.29
Aggregate	-56.29	3.58	-52.71
Het. sourcing	-56.10	3.32	-52.78
Het. emission bias	-56.23	3.10	-53.13
Panel F: Carbon price of 500 €/t CO_2			
Baseline	-260.20	-3.25	-263.46
Aggregate	-116.43	7.71	-108.72
Het. sourcing	-115.68	7.03	-108.65
Het. emission bias	-116.21	6.66	-109.55

Notes: The table reports the change in real income (Col. 1), disutility of emissions (Col. 2), and welfare (Col. 3) for a carbon tariff based on the emission intensity of firm imports. The carbon tariff applies the domestic carbon price, ranging from 14 to 500 €/t CO_2. All values are in billion €.

Table A.14: Decomposition for Different Import Prices

	EI (1)	Output (2)	Imports (3)	EII (4)	Total (5)
Panel A: Carbon price of 14 €/t CO_2					
Baseline	0.43	1.61	-1.21	-0.02	0.81
Aggregate	0.51	-0.11	-2.25	0.00	-1.85
Het. sourcing	0.36	0.32	-2.40	-0.01	-1.74
Het. emission bias	0.38	0.30	-2.29	0.00	-1.61
Panel B: Carbon price of 50 €/t CO_2					
Baseline	1.50	5.65	-4.28	-0.06	2.81
Aggregate	1.79	-0.39	-7.88	0.00	-6.48
Het. sourcing	1.25	1.12	-8.37	-0.05	-6.06
Het. emission bias	1.33	1.05	-8.00	0.00	-5.63
Panel C: Carbon price of 100 €/t CO_2					
Baseline	2.93	11.05	-8.45	-0.12	5.46
Aggregate	3.47	-0.75	-15.31	0.00	-12.59
Het. sourcing	2.45	2.17	-16.21	-0.09	-11.75
Het. emission bias	2.57	2.03	-15.54	0.00	-10.93
Panel D: Carbon price of 150 €/t CO_2					
Baseline	4.29	16.23	-12.52	-0.18	7.94
Aggregate	5.04	-1.08	-22.32	0.00	-18.38
Het. sourcing	3.59	3.16	-23.56	-0.14	-17.09
Het. emission bias	3.73	2.95	-22.66	0.00	-15.94
Panel E: Carbon price of 200 €/t CO_2					
Baseline	5.60	21.18	-16.47	-0.23	10.27
Aggregate	6.53	-1.40	-28.95	0.00	-23.86
Het. sourcing	4.69	4.09	-30.47	-0.18	-22.11
Het. emission bias	4.82	3.82	-29.37	0.00	-20.68
Panel F: Carbon price of 500 €/t CO_2					
Baseline	12.44	46.99	-38.07	-0.56	21.68
Aggregate	13.83	-2.95	-62.15	0.00	-51.40
Het. sourcing	10.42	8.76	-64.41	-0.44	-46.87
Het. emission bias	10.17	8.11	-62.90	0.00	-44.40

Notes: The table reports the decomposition of the change in global emissions into changes in emission intensity (Col. 1), output (Col. 2), offshoring (Col. 3), and the emission intensity of imports (Col. 4) for a carbon tariff based on the emission intensity of firm imports. The carbon tariff applies the domestic carbon price, ranging from 14 to 500 €/t CO_2. All values are in million t CO_2.

Table A.15: Effect on Emissions for Different Carbon Prices and an Industry Carbon Tariff

	Change in Emissions (%)			
	Domestic (1)	Foreign (2)	Global (3)	Leakage Rate (4)
Panel A: Carbon price of 14 €/t CO_2				
Baseline	-0.69	-0.12	-0.45	-0.14
Aggregate	-1.05	-0.66	-0.88	-0.48
Het. sourcing	-0.99	-0.61	-0.83	-0.47
Het. emission bias	-1.10	-0.66	-0.91	-0.45
Panel B: Carbon price of 50 €/t CO_2				
Baseline	-10.23	2.07	-4.94	0.15
Aggregate	-10.34	-0.34	-6.04	-0.02
Het. sourcing	-10.32	0.59	-5.63	0.04
Het. emission bias	-11.33	-0.15	-6.52	-0.01
Panel C: Carbon price of 100 €/t CO_2				
Baseline	-20.96	4.65	-9.94	0.17
Aggregate	-20.85	-0.17	-11.96	-0.01
Het. sourcing	-20.86	1.84	-11.09	0.07
Het. emission bias	-22.75	0.22	-12.87	0.01
Panel D: Carbon price of 150 €/t CO_2				
Baseline	-29.52	6.80	-13.90	0.17
Aggregate	-29.30	-0.28	-16.81	-0.01
Het. sourcing	-29.30	2.71	-15.53	0.07
Het. emission bias	-31.81	0.29	-18.00	0.01
Panel E: Carbon price of 200 €/t CO_2				
Baseline	-36.48	8.61	-17.08	0.18
Aggregate	-36.23	-0.59	-20.89	-0.01
Het. sourcing	-36.21	3.26	-19.23	0.07
Het. emission bias	-39.14	0.13	-22.25	0.00
Panel F: Carbon price of 500 €/t CO_2				
Baseline	-60.45	15.26	-27.88	0.19
Aggregate	-60.59	-4.77	-36.57	-0.06
Het. sourcing	-60.41	2.73	-33.24	0.03
Het. emission bias	-64.16	-3.57	-38.09	-0.04

Notes: The table reports the percentage changes in domestic emissions (Col. 1), foreign emissions (Col. 2), global emissions (Col. 3), and the leakage rate (Col. 4) for a carbon price increase from 10 to 14-100 €/t CO_2 and a carbon tariff based on the aggregate emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. Column 5 shows the model bias in global emissions change relative to the baseline.

Table A.16: Welfare Effects for Different Carbon Prices and an Industry Carbon Tariff

	Real Income (1)	Emissions (2)	Welfare (3)
Panel A: Carbon price of 14 €/t CO_2			
Baseline	-13.32	0.35	-12.97
Aggregate	-8.99	0.69	-8.30
Het. sourcing	-9.02	0.65	-8.37
Het. emission bias	-8.99	0.72	-8.27
Panel B: Carbon price of 50 €/t CO_2			
Baseline	-66.96	3.89	-63.07
Aggregate	-57.89	4.75	-53.13
Het. sourcing	-58.21	4.43	-53.78
Het. emission bias	-57.84	5.13	-52.71
Panel C: Carbon price of 100 €/t CO_2			
Baseline	-133.83	7.83	-126.00
Aggregate	-118.39	9.41	-108.97
Het. sourcing	-119.11	8.73	-110.38
Het. emission bias	-118.19	10.13	-108.05
Panel D: Carbon price of 150 €/t CO_2			
Baseline	-193.61	10.94	-182.67
Aggregate	-171.93	13.24	-158.68
Het. sourcing	-173.04	12.23	-160.81
Het. emission bias	-171.50	14.17	-157.32
Panel E: Carbon price of 200 €/t CO_2			
Baseline	-247.72	13.45	-234.26
Aggregate	-219.84	16.45	-203.39
Het. sourcing	-221.37	15.14	-206.23
Het. emission bias	-219.14	17.52	-201.62
Panel F: Carbon price of 500 €/t CO_2			
Baseline	-495.66	21.96	-473.70
Aggregate	-431.29	28.80	-402.49
Het. sourcing	-435.79	26.17	-409.61
Het. emission bias	-428.75	29.99	-398.75

Notes: The table reports the change in real income (Col. 1), disutility of emissions (Col. 2), and welfare (Col. 3) for a carbon price increase from 10 to 14-100 €/t CO_2 and a carbon tariff based on the aggregate emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. All values are in billion €.

Table A.17: Decomposition for Different Carbon Prices and an Industry Carbon Tariff

	EI (1)	Output (2)	Imports (3)	EII (4)	Total (5)
Panel A: Carbon price of 14 €/t CO_2					
Baseline	-3.04	0.99	-0.27	-0.01	-2.35
Aggregate	-3.20	0.07	-1.50	0.00	-4.63
Het. sourcing	-3.29	0.34	-1.37	-0.01	-4.34
Het. emission bias	-3.12	-0.18	-1.48	0.00	-4.78
Panel B: Carbon price of 50 €/t CO_2					
Baseline	-30.28	-0.36	4.70	-0.03	-25.94
Aggregate	-32.10	1.32	-0.76	0.00	-31.69
Het. sourcing	-32.08	1.35	1.36	-0.02	-29.53
Het. emission bias	-30.70	-3.55	-0.34	0.00	-34.23
Panel C: Carbon price of 100 €/t CO_2					
Baseline	-61.15	-1.90	10.56	-0.06	-52.21
Aggregate	-64.63	2.88	-0.39	0.00	-62.77
Het. sourcing	-64.50	2.72	4.21	-0.04	-58.20
Het. emission bias	-61.92	-7.69	0.50	0.00	-67.55
Panel D: Carbon price of 150 €/t CO_2					
Baseline	-86.01	-3.10	15.44	-0.09	-72.95
Aggregate	-90.62	4.27	-0.63	0.00	-88.27
Het. sourcing	-90.45	4.04	6.18	-0.06	-81.52
Het. emission bias	-87.04	-11.32	0.66	0.00	-94.48
Panel E: Carbon price of 200 €/t CO_2					
Baseline	-106.44	-3.99	19.57	-0.11	-89.69
Aggregate	-111.82	5.52	-1.33	0.00	-109.69
Het. sourcing	-111.63	5.32	7.45	-0.09	-100.93
Het. emission bias	-107.66	-14.55	0.28	0.00	-116.79
Panel F: Carbon price of 500 €/t CO_2					
Baseline	-178.57	-4.84	34.78	-0.30	-146.37
Aggregate	-185.44	11.13	-10.78	0.00	-191.99
Het. sourcing	-185.33	12.36	6.38	-0.22	-174.49
Het. emission bias	-180.30	-28.52	-8.07	0.00	-199.97

Notes: The table reports the decomposition of the change in global emissions into changes in emission intensity (Col. 1), output (Col. 2), offshoring (Col. 3), and the emission intensity of imports (Col. 4) for a carbon price increase from 10 to 14-100 €/t CO_2 and a carbon tariff based on the aggregate emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. All values are in million t CO_2.

Table A.18: Effect on Emissions for Different Carbon Prices and a Carbon Tariff

	Change in Emissions (%)			
	Domestic (1)	Foreign (2)	Global (3)	Leakage Rate (4)
Panel A: Carbon price of 14 €/t CO_2				
Baseline	-0.68	-0.12	-0.44	-0.13
Aggregate	-1.05	-0.66	-0.88	-0.48
Het. sourcing	-0.99	-0.61	-0.83	-0.47
Het. emission bias	-1.10	-0.66	-0.91	-0.45
Panel B: Carbon price of 50 €/t CO_2				
Baseline	-10.21	2.09	-4.92	0.15
Aggregate	-10.34	-0.34	-6.04	-0.02
Het. sourcing	-10.32	0.59	-5.62	0.04
Het. emission bias	-11.33	-0.15	-6.52	-0.01
Panel C: Carbon price of 100 €/t CO_2				
Baseline	-20.92	4.70	-9.90	0.17
Aggregate	-20.85	-0.17	-11.96	-0.01
Het. sourcing	-20.85	1.84	-11.09	0.07
Het. emission bias	-22.75	0.22	-12.87	0.01
Panel D: Carbon price of 150 €/t CO_2				
Baseline	-29.46	6.87	-13.83	0.18
Aggregate	-29.30	-0.28	-16.81	-0.01
Het. sourcing	-29.30	2.70	-15.53	0.07
Het. emission bias	-31.81	0.29	-18.00	0.01
Panel E: Carbon price of 200 €/t CO_2				
Baseline	-36.41	8.71	-17.00	0.18
Aggregate	-36.23	-0.59	-20.89	-0.01
Het. sourcing	-36.21	3.25	-19.22	0.07
Het. emission bias	-39.14	0.13	-22.25	0.00
Panel F: Carbon price of 500 €/t CO_2				
Baseline	-60.35	15.50	-27.72	0.19
Aggregate	-60.59	-4.77	-36.57	-0.06
Het. sourcing	-60.40	2.71	-33.24	0.03
Het. emission bias	-64.16	-3.57	-38.09	-0.04

Notes: The table reports the percentage changes in domestic emissions (Col. 1), foreign emissions (Col. 2), global emissions (Col. 3), and the leakage rate (Col. 4) for a carbon price increase from 10 to 14-100 €/t CO_2 and a carbon tariff based on the emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. Column 5 shows the model bias in global emissions change relative to the baseline.

Table A.19: Welfare Effects for Carbon Prices and a Carbon Tariff

	Real Income (1)	Emissions (2)	Welfare (3)
Panel A: Carbon price of 14 €/t CO_2			
Baseline	-13.41	0.35	-13.07
Aggregate	-8.99	0.69	-8.30
Het. sourcing	-9.02	0.65	-8.37
Het. emission bias	-8.99	0.72	-8.27
Panel B: Carbon price of 50 €/t CO_2			
Baseline	-67.27	3.87	-63.40
Aggregate	-57.89	4.75	-53.13
Het. sourcing	-58.20	4.43	-53.77
Het. emission bias	-57.84	5.13	-52.71
Panel C: Carbon price of 100 €/t CO_2			
Baseline	-134.44	7.79	-126.64
Aggregate	-118.39	9.41	-108.97
Het. sourcing	-119.09	8.73	-110.36
Het. emission bias	-118.19	10.13	-108.05
Panel D: Carbon price of 150 €/t CO_2			
Baseline	-194.49	10.89	-183.60
Aggregate	-171.93	13.24	-158.68
Het. sourcing	-173.02	12.23	-160.79
Het. emission bias	-171.50	14.17	-157.32
Panel E: Carbon price of 200 €/t CO_2			
Baseline	-248.84	13.39	-235.46
Aggregate	-219.84	16.45	-203.39
Het. sourcing	-221.34	15.14	-206.20
Het. emission bias	-219.14	17.52	-201.62
Panel F: Carbon price of 500 €/t CO_2			
Baseline	-497.88	21.83	-476.06
Aggregate	-431.29	28.80	-402.49
Het. sourcing	-435.74	26.17	-409.57
Het. emission bias	-428.75	29.99	-398.75

Notes: The table reports the change in real income (Col. 1), disutility of emissions (Col. 2), and welfare (Col. 3) for a carbon price increase from 10 to 14-100 €/t CO_2 and a carbon tariff based on the emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. All values are in billion €.

Table A.20: Decomposition for Carbon Prices and a Carbon Tariff

	EI (1)	Output (2)	Imports (3)	EII (4)	Total (5)
Panel A: Carbon price of 14 €/t CO_2					
Baseline	-3.04	1.01	-0.25	-0.01	-2.31
Aggregate	-3.20	0.07	-1.50	0.00	-4.63
Het. sourcing	-3.29	0.35	-1.38	-0.01	-4.34
Het. emission bias	-3.12	-0.18	-1.48	0.00	-4.78
Panel B: Carbon price of 50 €/t CO_2					
Baseline	-30.28	-0.28	4.75	-0.03	-25.81
Aggregate	-32.10	1.32	-0.76	0.00	-31.69
Het. sourcing	-32.08	1.37	1.36	-0.02	-29.53
Het. emission bias	-30.70	-3.55	-0.34	0.00	-34.23
Panel C: Carbon price of 100 €/t CO_2					
Baseline	-61.15	-1.73	10.66	-0.05	-51.96
Aggregate	-64.63	2.88	-0.39	0.00	-62.77
Het. sourcing	-64.51	2.74	4.20	-0.04	-58.20
Het. emission bias	-61.92	-7.69	0.50	0.00	-67.55
Panel D: Carbon price of 150 €/t CO_2					
Baseline	-86.01	-2.85	15.60	-0.07	-72.60
Aggregate	-90.62	4.27	-0.63	0.00	-88.27
Het. sourcing	-90.46	4.07	6.16	-0.06	-81.51
Het. emission bias	-87.04	-11.32	0.66	0.00	-94.48
Panel E: Carbon price of 200 €/t CO_2					
Baseline	-106.43	-3.66	19.78	-0.10	-89.24
Aggregate	-111.82	5.52	-1.33	0.00	-109.69
Het. sourcing	-111.64	5.37	7.43	-0.08	-100.93
Het. emission bias	-107.66	-14.55	0.28	0.00	-116.79
Panel F: Carbon price of 500 €/t CO_2					
Baseline	-178.56	-4.10	35.30	-0.26	-145.52
Aggregate	-185.44	11.13	-10.78	0.00	-191.99
Het. sourcing	-185.34	12.45	6.33	-0.20	-174.50
Het. emission bias	-180.30	-28.52	-8.07	0.00	-199.97

Notes: The table reports the decomposition of the change in global emissions into changes in emission intensity (Col. 1), output (Col. 2), offshoring (Col. 3), and the emission intensity of imports (Col. 4) for a carbon price increase from 10 to 14-100 €/t CO_2 and a carbon tariff based on the emission intensity of imports. The carbon tariff prices emissions at the domestic carbon price. All values are in million t CO_2.

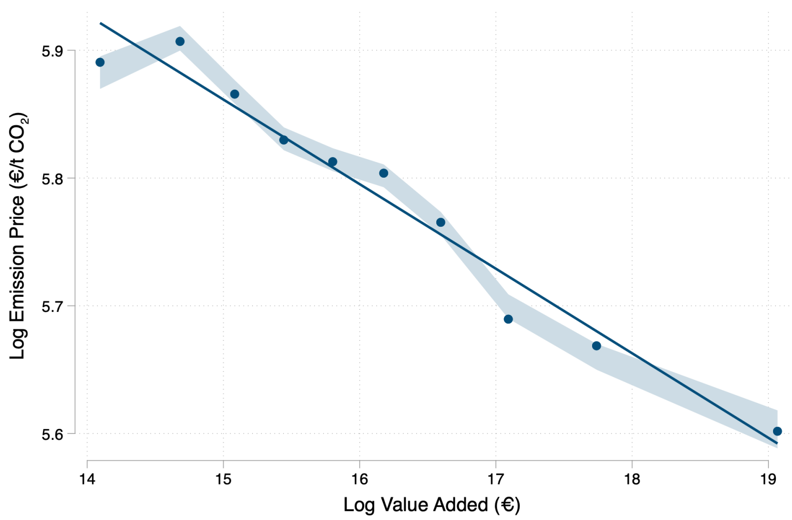
Table A.21: Emission Factors for German Fuels

	2011	2012	2013	2014	2015	2016	2017	2018	2019
Coke	389,20	389,20	389,20	389,20	389,20	389,20	389,20	389,20	389,20
Light fuel oil	266,50	266,50	266,50	266,50	266,50	266,50	266,50	266,50	266,50
Heavy fuel	288,50	288,50	288,50	288,50	288,50	288,50	288,50	288,50	288,50
Other petroleum products	281,50	281,50	281,50	281,50	281,50	281,50	281,50	281,50	281,50
Natural gas	201,30	201,30	201,30	201,30	201,30	201,30	201,30	201,30	201,30
Liquified gas	236,20	236,20	236,20	236,20	236,20	236,20	236,20	236,20	236,20
Other gas products	196,50	196,50	196,50	196,50	196,50	196,50	196,50	196,50	196,50
Industrial waste and other fuels	256,00	256,00	256,00	256,00	256,00	256,00	256,00	256,00	256,00
Renewables	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Raw lignite	381,70	377,90	378,50	373,60	374,20	380,80	382,50	382,90	383,30
Hard coal	339,20	337,20	336,10	336,80	336,60	336,80	336,10	335,10	337,20
Brown coal briquettes	357,40	357,40	356,70	358,40	357,80	358,20	357,50	356,40	356,30
Other coal products	353,20	352,90	352,90	353,10	352,80	352,90	353,10	351,00	350,90
District heat	188,10	187,50	186,80	186,20	185,60	185,00	184,40	183,70	183,10
Electricity	568,00	573,00	572,00	557,00	527,00	523,00	488,00	471,00	408,00

Notes: Emission factors are taken from Umweltbundesamt (2008), Umweltbundesamt (2021), and Umweltbundesamt (2022) reported in gCO_2/kWh.

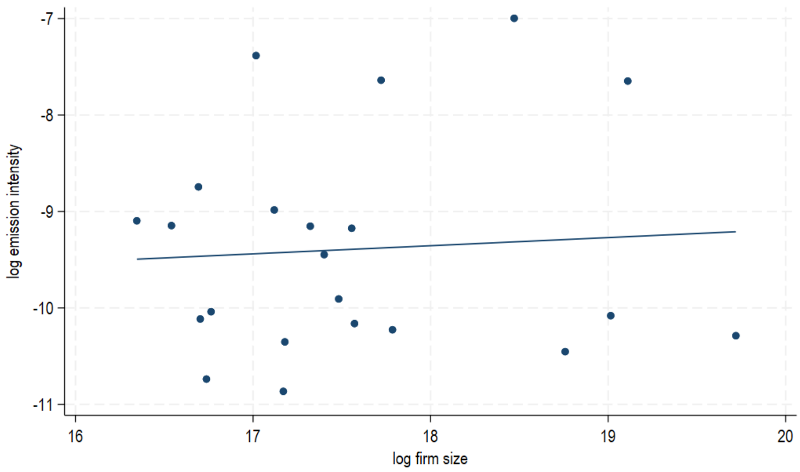
A.6 Additional Figures

Figure A.3: Firm Size and the Implicit Emission Price

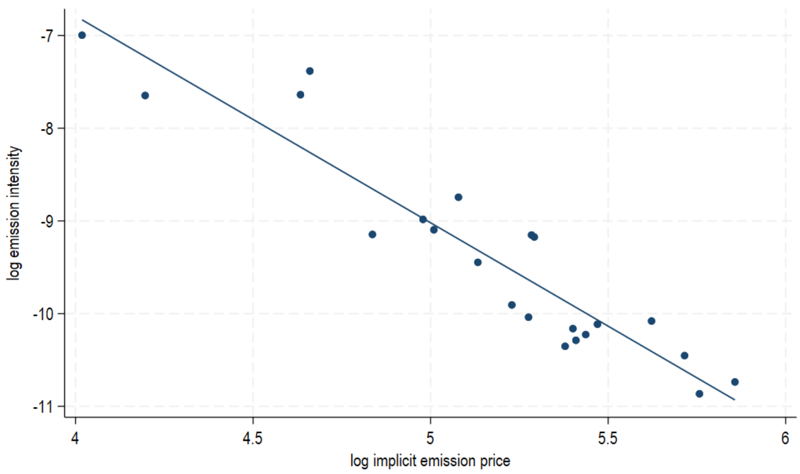


Notes: This figure depicts a binscatter plot of log(implicit emission price) as the dependent variable and log(value added) as the independent variable, controlling for four-digit industry and year fixed effects. Observations are divided into ten equal-sized bins using the independent variable. For each bin, the mean of the dependent variable and the mean of the independent variable are computed. The data for the dependent variable is residualized. Implicit emission price is defined as the energy expenditure divided by the emissions resulting from fuel use and electricity. For the plot, the years 2011-2018 are used.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.4: Correlation of Emission Intensity With Industry Outcomes



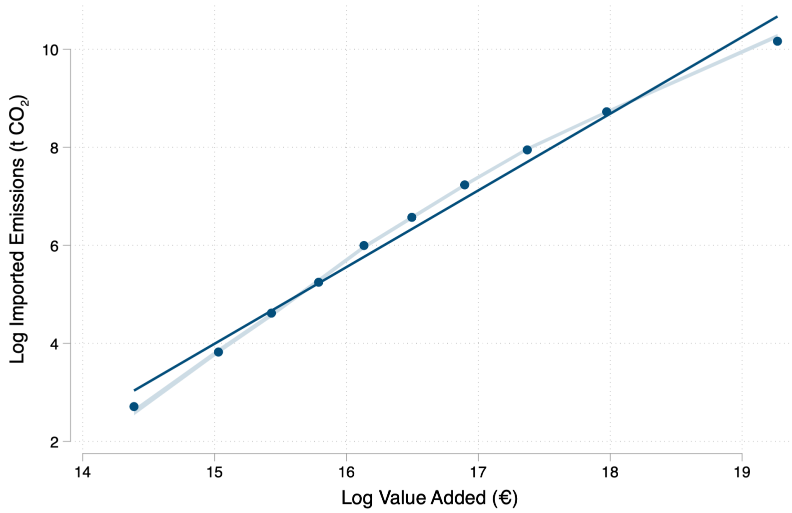
(a) Emission Intensity and Sales



(b) Emission Intensity and Implicit Emission Prices

Notes: Panel (a) plots log(emission intensity) as the dependent variable and log(average firm size) as the independent variable for two-digit industries in the German manufacturing sector. Panel (b) plots log(emission intensity) as the dependent variable and log(average implicit emission price) as the independent variable for two-digit industries in the German manufacturing sector. Emission intensity is defined as emissions divided by sales. The implicit emission price is defined as energy expenditure divided by emissions from fuel use and electricity. Firm size is measured by sales. For the plot, the years 2011-2018 are used.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

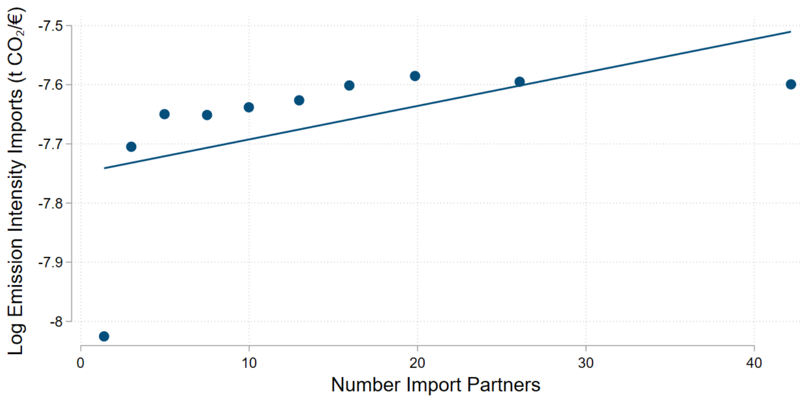
Figure A.5: Firm Size and Imported Emissions



Notes: This figure depicts a binscatter plot of log(imported emissions) as the dependent variable and log(value added) as the independent variable, controlling for four-digit industry and year fixed effects. Observations are divided into ten equal-sized bins using the independent variable. For each bin, the mean of the independent variable and the mean of the dependent variable are computed. The data for the dependent variable is residualized. Imported emissions are defined as the direct and indirect emissions of imports. For the plot, the years 2011-2018 are used.

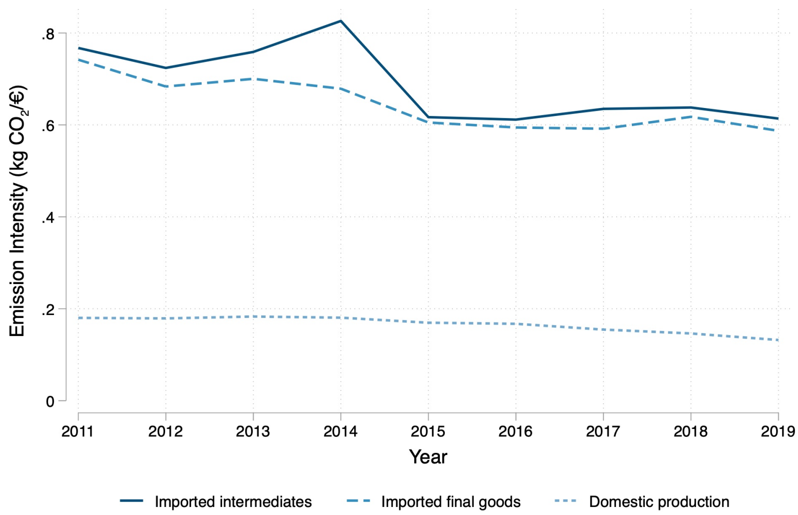
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.6: Emission Intensity of Imports and Number of Importing Countries

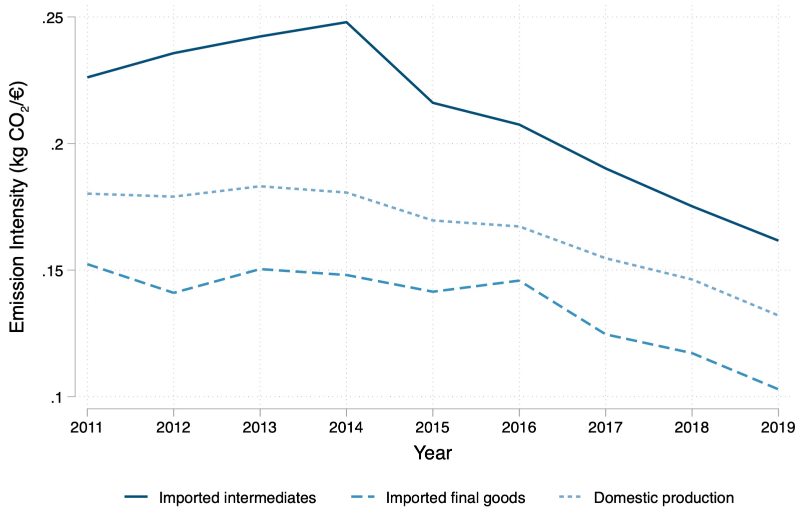


Notes: This figure depicts a binscatter plot of log(emission intensity of imports) as the dependent variable and the number of different partner countries as the independent variable, controlling for four-digit industry and year fixed effects. Observations are divided into ten equal-sized bins using the independent variable. For each bin, the mean of the independent variable and the mean of the dependent variable are computed. The data for the dependent variable is residualized. The emission intensity of imports is defined as the direct and indirect emissions of imports divided by value added. For the plot, the years 2011-2018 are used.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.7: Emission Intensity of Domestic Production and Imports



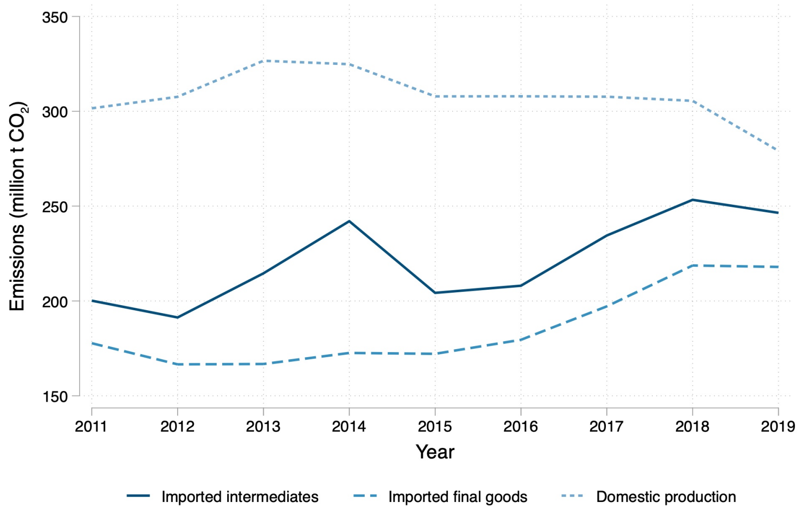
(a) Exiobase



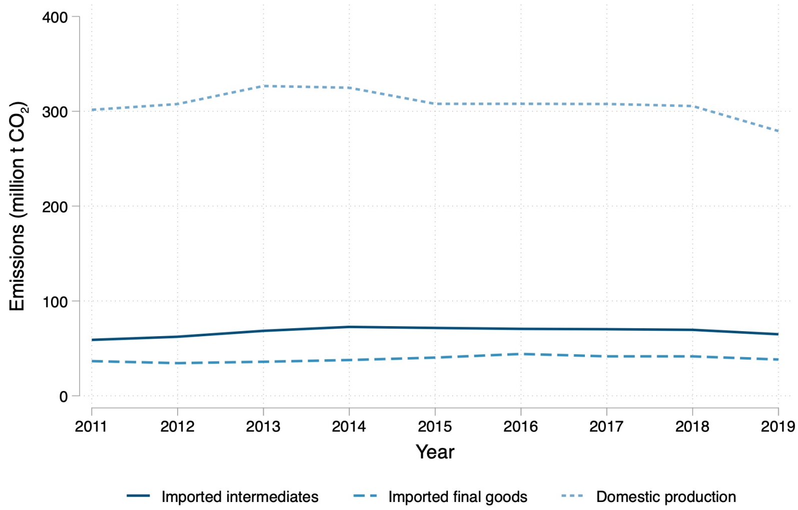
(b) Domestic emission intensity

Notes: This figure shows the emission intensity (in kg CO_2) for imported intermediates, imported final goods, and domestic production from 2011 to 2019. The emission intensity of domestic production is based on German firm data. In Panel (a), emissions of imported goods are calculated as the product of import emission intensities from Exiobase and the value of imports. In Panel (b), emissions of imported goods are calculated using domestic emission intensities multiplied by the value of imports.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.8: Domestic and Imported Emissions



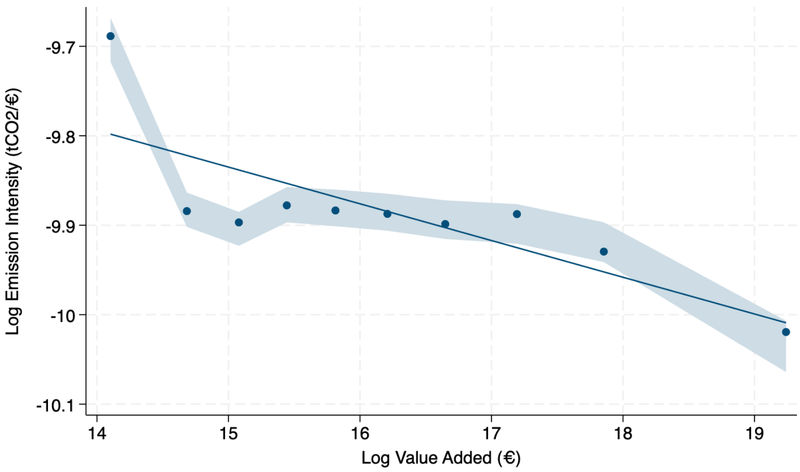
(a) Exiobase



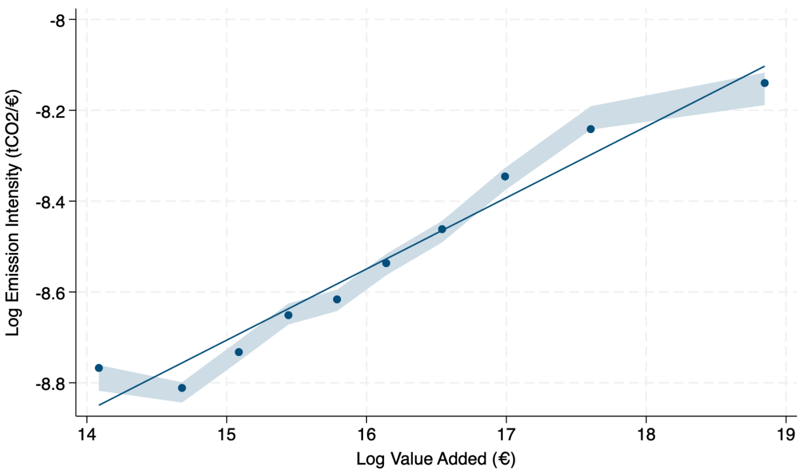
(b) Domestic emission intensity

Notes: This figure shows emissions (in million tons CO_2) for imported intermediates, imported final goods, and domestic production between 2011 and 2019. In Panel (a), emissions of imported goods are calculated as the product of import emission intensities from Exiobase and the value of imports. In Panel (b), emissions of imported goods are calculated using domestic emission intensities multiplied by the value of imports.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.9: Emission Intensity for Clean and Dirty Industries



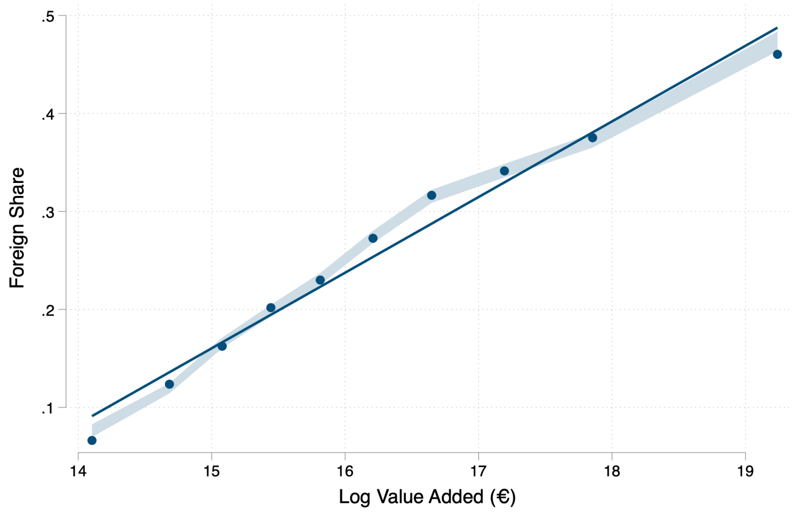
(a) Clean



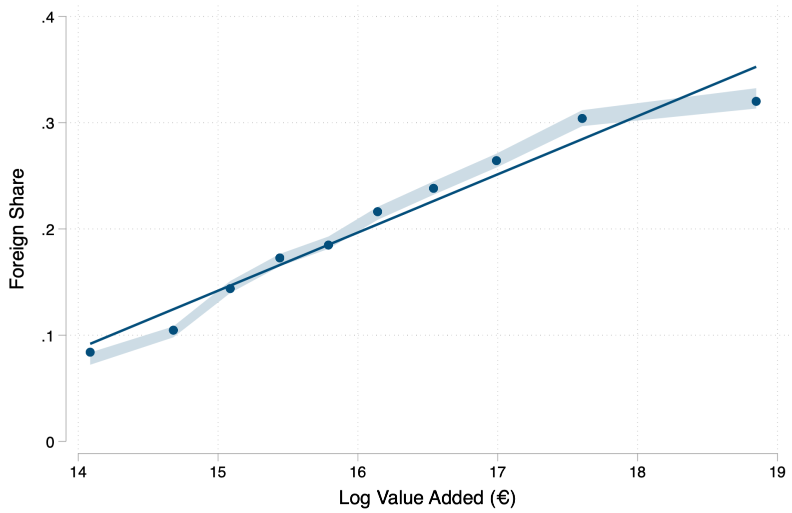
(b) Dirty

Notes: This figure presents binscatter plots of log(emission intensity) on the y-axis and log(value added) on the x-axis, controlling for four-digit industry and year fixed effects. Observations are grouped into ten equally sized bins based on value-added, with the mean calculated for each bin. Data for the dependent variable are residualized. Panel (a) shows the binscatter for firms in clean industries, while panel (b) shows the binscatter for firms in dirty industries. An industry is classified as dirty if its emission intensity is above the median emission intensity across all industries. Emission intensity is measured as tons of CO_2 emissions divided by value added. The data cover the years 2011–2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.10: Foreign Share for Clean and Dirty Industries



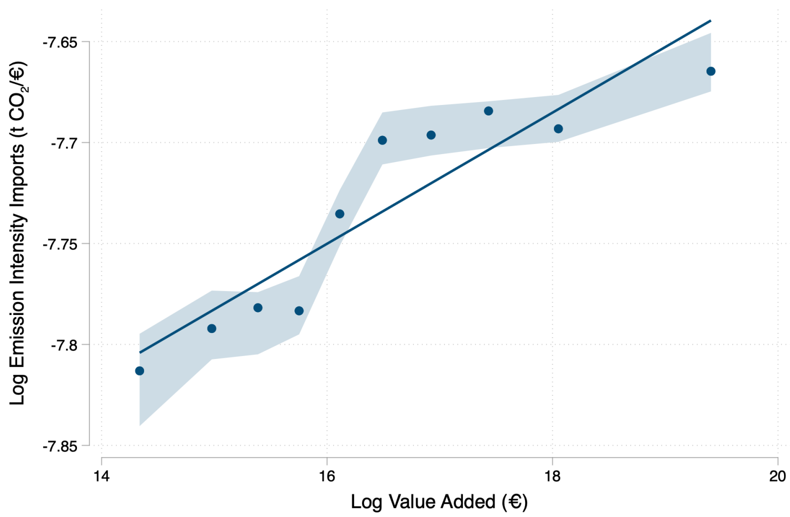
(a) Clean



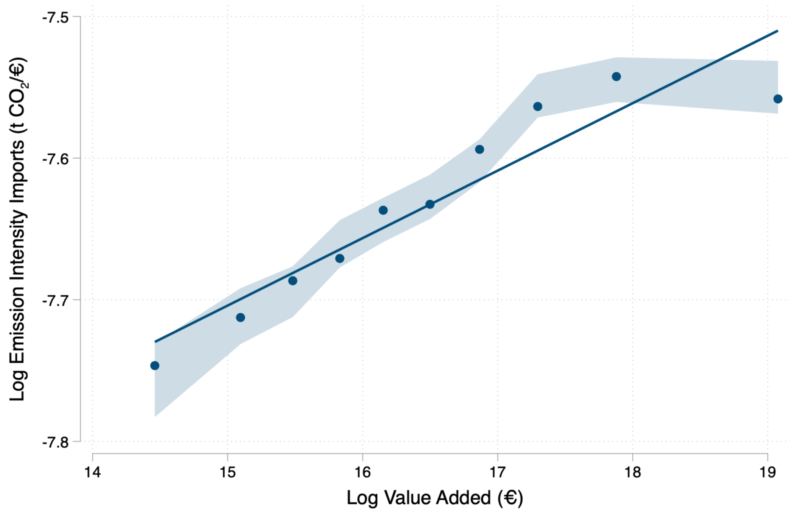
(b) Dirty

Notes: This figure presents binscatter plots of the foreign share on the y-axis and log(value added) on the x-axis, controlling for four-digit industry and year fixed effects. Observations are grouped into ten equally sized bins based on value-added, with the mean calculated for each bin. Data for the dependent variable are residualized. Panel (a) shows the binscatter for firms in clean industries, while panel (b) shows the binscatter for firms in dirty industries. An industry is classified as dirty if its emission intensity is above the median emission intensity across all industries. The foreign share is defined as imports excluding raw materials divided by expenditures on intermediate inputs. The data cover the years 2011–2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.11: Emission Intensity of Imports for Clean and Dirty Industries



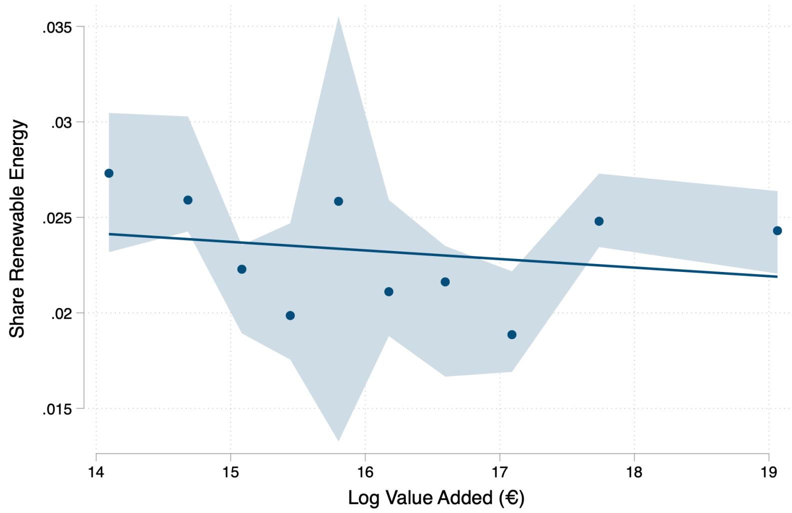
(a) Clean



(b) Dirty

Notes: This figure presents binscatter plots of log(import emission intensity) (EII) on the y-axis and log(value added) on the x-axis, controlling for four-digit industry and year fixed effects. Observations are grouped into ten equally sized bins based on value-added, with the mean calculated for each bin. Data for the dependent variable are residualized. Panel (a) shows the binscatter for firms in clean industries, while panel (b) shows the binscatter for firms in dirty industries. An industry is classified as dirty if its emission intensity is above the median emission intensity across all industries. The emission intensity of imports is defined as the sum of direct and indirect emissions divided by value added. The data cover the years 2011–2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Figure A.12: Firm Size and Renewable Energy Share



Notes: This figure depicts a binscatter plot of the share of renewable energy as the dependent variable and log(value added) as the independent variable, controlling for four-digit industry and year fixed effects. Observations are divided into ten equal-sized bins using the independent variable. For each bin, the mean of the independent variable and the mean of the dependent variable are computed. The data for the dependent variable is residualized. The share of renewable energy is defined as the proportion of total energy and electricity use that comes from renewable sources. For the plot, the years 2011-2018 are used.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Außenhandelsstatistik 2011–2019, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

2 Designing Effective Carbon Border Adjustment with Minimal Information Requirements

Joint with Alessia Campolmi, Harald Fadinger, Chiara Forlati and Ulrich J. Wagner

2.1 Introduction

Only one quarter of greenhouse gas (GHG) emissions worldwide are subject to carbon taxes or cap-and-trade policies (World Bank, 2024). Differences in carbon prices across countries encourage carbon leakage by shifting comparative advantage in the production of carbon-intensive goods to countries with lax policies. Because leakage undermines global mitigation efforts, preventing it is a priority for countries pursuing ambitious climate policies.

The economically-preferred policy is to 'level the playing field' on domestic and export markets by taxing imports and subsidizing exports at the prevailing carbon price, based on the embedded emissions (Hoel, 1996; Markusen, 1975). Such border carbon adjustments have long been regarded as incompatible with the rules of the World Trade Organization (WTO). This paradigm has shifted with the recent launch of the EU's Carbon Border Adjustment Mechanism (CBAM), which was prompted by strong and persistent increases in carbon prices under the EU Emissions Trading System (EU-ETS). Starting in 2026, the EU will levy tariffs on imports based on embedded carbon emissions, at a rate pegged to the EU-ETS price. CBAM tariffs discourage the replacement of EU production with dirty imports (import leakage) and partially correct for the absence of carbon taxes abroad (Böhringer et al., 2022). Conceptually, CBAM improves over current policies granting overly generous subsidies to EU producers in trade-exposed sectors (Martin et al., 2014). In practice, however, CBAM is complicated by excessive information requirements for computing embedded emissions, a discriminatory tariff structure that prominent trade partners of the EU have repeatedly denounced as punitive, protectionist, and incompatible with WTO rules,[1] as well as incomplete coverage that distorts global value chains (Draghi, 2024).

Using a state-of-the-art quantitative economic model of international trade, we assess the impacts of CBAM on bilateral trade flows, global emissions, and welfare. A key insight is that border adjustments must be applied to *all* –not just a subset– of industries to effectively

[1] For example, the ten BRICS nations recently declared: "We reject unilateral, punitive and discriminatory protectionist measures, that are not in line with international law, under the pretext of environmental concerns, such as unilateral and discriminatory carbon border adjustment mechanisms (CBAMs)." (BRICS, 2025, paragraph 88). Many countries have raised concerns about CBAM with the WTO's Committee on Market Access (WTO, 2024) and its Council for Trade in Goods (WTO, 2023) on multiple occasions.

prevent carbon leakage. Universally applying CBAM tariffs would also substantially lower the EU welfare costs of carbon pricing, but it would do so by significantly restricting access to EU markets for the many trade partners where production is more carbon-intensive.

We propose a simple alternative to CBAM that is universally applicable due to its low information requirements and effectively prevents carbon leakage with minimal impacts on international trade: The Leakage Border Adjustment Mechanism (LBAM) implements product-specific import tariffs that exactly offset the changes in EU imports resulting from an increase in the carbon price differential between the EU and its trade partners. Knowledge of foreign carbon intensities is not needed to compute LBAM tariffs, making them easy to implement. Since LBAM tariffs do not discriminate across countries and minimize interference with international trade patterns, they are also easier to accept for Europe's trade partners than CBAM tariffs. Furthermore, our analysis shows that most carbon leakage arises from EU producers losing market share on export markets, an issue not addressed by CBAM. Extending the LBAM principle to export subsidies would prevent this type of leakage.

To characterize and quantify the trade, welfare and emission effects of unilateral carbon pricing in the EU under alternative border adjustment scenarios, we develop a tractable structural model of international trade in differentiated products with many sectors and countries. We regard the EU as the domestic economy that unilaterally implements a carbon price and a border adjustment mechanism. Consumers derive utility from bundles of differentiated product varieties offered by monopolistically-competitive firms. Firms have market-specific production functions with sector-specific returns to scale, so that production decisions can be separated across markets and export supply curves have sector-specific slopes. Given the short-run nature of our model, we assume that the number of firms is fixed. Carbon emissions are embodied in a composite energy input to production, along with physical factors. Emissions are thus a by-product of production, which can be reduced with carbon taxes. Carbon emissions constitute a global public bad whose social marginal cost does not depend on the place of emission.

Our model allows deriving simple closed-form expressions for LBAM tariffs and export subsidies that undo changes in imports and exports resulting from any given change in the EU's carbon price (and the related energy price change) without interfering with fluctuations in EU trade driven by unrelated shocks. For any given sector, LBAM tariffs depend only on readily available information and structural parameters: the EU's absorption share falling on EU-produced goods; the EU's import demand elasticity; the foreign export supply elasticity; and the output to energy elasticity. Similarly, LBAM export subsidies depend only on the latter two objects and undo fluctuations in EU export prices driven by changes in the EU carbon price.

For our quantitative analysis, we calibrate the model using comprehensive data on demand and supply in 131 4-digit manufacturing sectors for the year 2018. Sector-level price elasticities of import demand and export supply are estimated on bilateral trade flows between the EU27 and 56 other countries following Broda and Weinstein (2006) and Feenstra (1994) and Soderbery (2015). Sectoral output elasticities of energy and physical production factors are obtained via the estimation of sector-specific production functions using detailed firm-level micro-data for Germany (Ackerberg et al., 2015; Wooldridge, 2009). We solve for an initial equilibrium with a low carbon price of 15 dollars per ton (the average EU ETS price in 2018) and one with a high carbon price of 105 dollars per ton (the approximate average price in 2023. Following Dekle et al. (2007), we replace equilibrium objects that depend on unknown parameters with bilateral trade flows and absorption data constructed by combining trade data with 4-digit production data. To compare LBAM with CBAM, and to evaluate the effect of EU policies on global emissions, we also require estimates of foreign emission intensities. We use our model in combination with newly compiled, comprehensive data on energy prices and the average fuel mix of manufacturing companies to construct emissions intensities in each country.

With this model in hand, we quantify the impacts of an increase in the EU's carbon price from \$15 to \$105 on EU welfare and global emissions. In the absence of border adjustments (no-BAM), this seven-fold increase in the carbon price reduces global emissions by just 0.85% while leading to significant welfare losses of \$25 bn for the EU because the economic costs of around \$ 57 bn outweigh the environmental benefits of \$ 32 bn. Carbon leakage is manifest in sizable displacements of EU manufacturing production by dirty imports to the EU and by dirty exports of third countries to the rest of the world. For the average sector, EU imports increase by 11% and EU exports fall by 9.4%,

We analyze how different border adjustments affect welfare and emissions, relative to this reference case. An 'ideal' CBAM that covers all sectors and taxes all imports based on their (truthfully reported) carbon content would imply welfare gains for the EU and increase global abatement by 70%, to 1.43% of global emissions. A comprehensive CBAM where carbon tariffs are based on the EU emission intensity of the sector instead of the foreign one would fare almost as well. However, the current EU proposal limits CBAM tariffs to very few sectors which, in our simulations, improves only marginally upon the no-BAM case: global abatement rises from 0.85% to 0.87% and EU welfare losses remain similar to the reference scenario. In contrast, our proposed LBAM policies deliver much stronger emissions reductions because they directly target leakage. An LBAM tariff that adjusts for import leakage increases global abatement to 0.97% and almost halves EU welfare losses compared to the no-BAM case. Global abatement can be further raised to 1.28% and EU welfare losses reduced to \$ 4 bn when LBAM additionally grants export subsidies to prevent leakage on export markets. This closes three quarters of the gap to the ideal CBAM while minimizing information requirements and political backlash from the EU's trading partners; the magnitudes of non-discriminatory LBAM tariffs and export subsidies are modest, averaging at 1.3 % and 3.7 %, respectively.

The literature on border adjustment mechanisms (BAMs) predominantly employs computable general equilibrium models (Böhringer et al., 2022)–a powerful tool that has limitations when it comes to including industry-specific detail (Fowlie and Reguant, 2022) and to transparently connecting theory and data (Costinot and Rodríguez-Clare, 2014). Recent empirical studies of environmental regulation and emissions leakage showcase the benefits of using modern structural trade models in this context (Aichele and Felbermayr, 2015; Larch and Wanner, 2017; Shapiro and Walker, 2018; Sogalla, 2023; Stillger, 2025). Adopting this approach allows us to derive closed-form expressions of all border taxes and subsidies considered, based on highly granular data for 131 sectors and 83 countries. Related research has evaluated the effects of CBAM for a smaller set of industries (Ambec et al., 2024) or derived empirically-based *production* subsidies to mitigate leakage (Fowlie and Reguant, 2022). Our focus on implementation constraints sets this analysis apart from that of unilaterally *optimal* BAMs (Farrokhi and Lashkaripour, 2025; Kortum and Weisbach, 2021), and our LBAM proposal is an alternative to mitigating CBAM's information asymmetries using mechanism design (Cicala et al., 2023).

The main contributions of our paper can be summarized as follows. First, we quantify the economic and environmental consequences of various carbon border adjustments, with the key results that the limited application of CBAM tariffs to a handful of sectors is environmentally ineffective, whereas a universal application of CBAM imposes large welfare costs on non-EU countries. Second, we propose an alternative border adjustment mechanism, LBAM, which effectively prevents carbon leakage and is better suited to overcome both legal and information constraints that plague other types of border carbon adjustments. Third, by explicitly considering export-driven carbon leakage within an LBAM framework, our analysis informs the political process of designing export subsidies which has just been initiated by the European Commission (2025).

The remainder of the paper is structured as follows. The next section summarizes the EU's CBAM policy and introduces the main idea behind LBAM, illustrated with simple graphical arguments. Section 2.3 develops a structural economic model and derives analytical results for how unilateral carbon pricing combined with different border adjustment mechanisms affect welfare and emissions. Section 2.4 explains the model calibration and discusses the underlying data. In Section 2.5, we present simulation results for studying the welfare, trade, and emission effects of an EU carbon price increase under various border adjustment scenarios. Section 2.6 examines the robustness of these results to alternative modeling assumptions. Section 2.7 concludes.

2.2 EU Carbon Pricing and Leakage Protection

In Europe, energy-intensive industries have been paying carbon prices since the launch of the EU-ETS in 2005. The EU-ETS permit price has been below 20 € for many years (Ellerman et al., 2016; Hintermann et al., 2016), but it climbed to over 100 € between October 2020 and February 2023, and has rarely fallen below 60 € since then. Against this background, and in view of the European Green Deal's increasingly ambitious climate policies, the EU Commission proposed the introduction of CBAM in July 2021.

2.2.1 The Carbon Border Adjustment Mechanism (CBAM)

CBAM applies to EU imports in a handful of very carbon-intensive industries considered at high risk of carbon leakage (iron and steel, cement, fertilizers, aluminum, hydrogen, and electricity). Starting in 2026, EU importers must buy a 'CBAM certificate' for each ton of CO_2 emissions embedded in those goods.[2] The certificate price is pegged to the weekly EU-ETS price, and can be deducted by pertinent carbon prices already paid in the origin country. This design establishes a level playing field between imports and domestic production, providing non-EU countries with an incentive to green their production processes.

A CBAM reporting system was launched in October 2023 to close immense information gaps before financial adjustments can be implemented. EU importers must calculate the actual, plant-specific CO_2 emissions in the origin country. Given the lack of such data (Fowlie and Reguant, 2018) and obvious incentives for under-reporting, the regulation stipulates that effective monitoring and verification processes be established. This creates a dilemma. On one hand, extending CBAM to all leakage-relevant sectors requires a large bureaucracy that is expensive to maintain for the EU and acts like a trade barrier towards its trade partners (Cosbey et al., 2019; Draghi, 2024). On the other hand, allowing importers to fall back on average carbon intensities in the exporting country or in the EU fails to level the playing field with respect to carbon costs and leads to other evasion problems (e.g., re-routing imports via 'clean' third countries).

There is an urgent need to fix these problems because CBAM's incomplete coverage misses embedded emissions of many unregulated products and threatens the competitiveness of

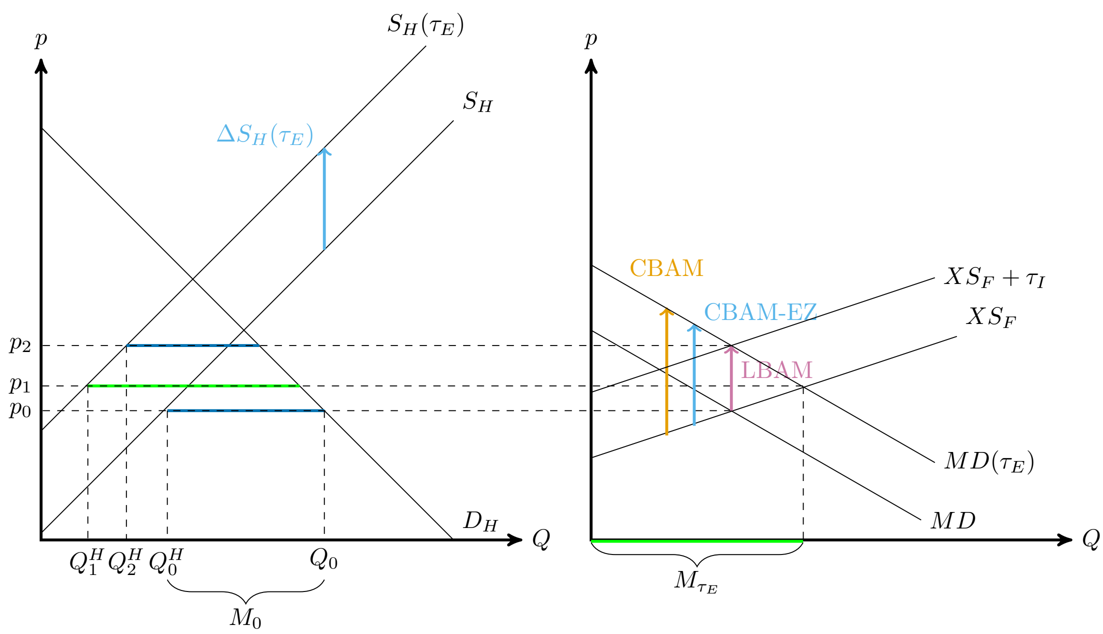
[2]Current draft legislation defers the start of actual payments to February 1, 2027, and introduces a new exemption threshold which further limits CBAM obligations to those companies importing more than 50 tons of CBAM goods per year (European Commission, 2025).

downstream industries in the EU (Draghi, 2024). For example, CBAM tariffs are levied on imported steel but not on imported cars. As a solution, we propose a border adjustment mechanism focused on leakage prevention, which keeps bureaucracy, compliance costs, and trade impacts to a minimum.

2.2.2 The Leakage Border Adjustment Mechanism (LBAM)

Figure 2.1 illustrates the workings of different border adjustment mechanisms in partial equilibrium with two countries, Home and Foreign. Home is a net importer of a good that it can produce at increasing marginal cost. The difference between Home's demand (D_H) and supply (S_H) curves for any given price p gives Home's import demand curve (MD). Foreign is characterized by an upward-sloping export supply curve XS_f. Under free trade, equilibrium obtains at the world price p_0 where domestic demand Q_0 is met by domestic supply Q_0^H and imports M_0 from Foreign. A carbon tax τ_E raised unilaterally in Home increases marginal production cost for any given quantity ($S_H(\tau_E)$). The equilibrium price rises to p_1 and imports increase to M_{τ_E} as they become cheaper relative to domestic production. This goes along with emissions 'leaking' from Home to Foreign.

Figure 2.1: Trade Effects of a Carbon Tax and Border Adjustment Mechanisms



Home can exactly offset carbon leakage by imposing a tariff τ_I ("LBAM") that cancels out the cost disadvantage of domestic producers generated by the domestic carbon tax. The tariff shifts out Foreign export supply ($XS_F + \tau_I$) and raises the consumer price in Home such that domestic production increases and import demand falls until imports are back at their initial level M_0. Global emissions fall with imports because, by assumption, production in Home is less carbon-intensive than in Foreign.

CBAM targets embedded emissions rather than leakage. A CBAM tariff based on Home's carbon intensity ("CBAM-EZ") shifts out Foreign's export supply curve by $\Delta S_H(\tau_E)$, the increment in Home's marginal cost due to the carbon tax. When based on Foreign's actual carbon intensity, the tariff would further increase ("CBAM"). Both CBAM tariffs reduce imports beyond what is needed to prevent carbon leakage because they tax all emissions embedded in domestic consumption. This foreshadows our quantitative result that CBAM tariffs reduce the welfare of non-EU countries. In contrast, LBAM does not hurt foreign exporters; it merely re-establishes the *status quo* before the unilateral carbon price increase.

2.3 Economic Model

To rigorously analyze these policies, we build a quantitative trade model that satisfies structural gravity (Costinot and Rodríguez-Clare, 2014). While LBAM eliminates carbon leakage, imports are also affected by demand and supply shocks that are unrelated to carbon pricing and hence should not be neutralized. Computing LBAM tariffs thus requires us to simulate changes in imports at different levels of the EU-ETS price while holding fixed the effects of other shocks. Our model transparently solves for LBAM instruments as closed-form functions of observable data and econometrically estimable parameters.

2.3.1 Model Setup

We solve a multi-country model with countries denoted by $i, j = 1, ..., I$. The first subindex denotes the location of consumption and the second one the location of production. In each country, there is a continuum of tradable sectors indexed by s.

Consumers We assume quasi-linear utility between a tradable outside sector and a Cobb-Douglas aggregate of a continuum of differentiated tradable sectors with weights η_{is}. Carbon emissions constitute a public bad with constant marginal social costs (SCC) θ_i. Utility of the representative consumer in country i is given by

$$U_i = C_{i0} + \int_s \eta_{is} \log C_{is} ds - \theta_i \int_s e_s ds, \tag{2.1}$$

where C_{i0} is the numéraire and

$$C_{is} = \left[\sum_{j=1}^{J} \int_0^{N_{ijs}} c_{ijs}(\omega)^{\frac{\varepsilon_s - 1}{\varepsilon_s}} d\omega \right]^{\frac{\varepsilon_s}{\varepsilon_s - 1}}$$

is a CES aggregator for sector-specific varieties ω. $c_{ijs}(\omega)$ denotes consumption of an individual variety ω produced in j. N_{ijs} is the (exogenous) measure of varieties produced by j available in i. The elasticity of substitution across varieties, $\varepsilon_s > 1$, is sector-specific. e_s denotes worldwide emissions of sector s. Standard calculations yield i's demand for sector-s varieties sourced from j

$$c_{ijs}(\omega) = \left(\frac{p_{ijs}(\omega)}{P_{ijs}} \right)^{-\varepsilon_s} C_{ijs}, \tag{2.2}$$

demand for the aggregate consumption bundle sourced from j

$$C_{ijs} = \left(\frac{P_{ijs}}{P_{is}} \right)^{-\varepsilon_s} C_{is} \tag{2.3}$$

and demand for the aggregate sector s bundle

$$C_{is} = \eta_{is} P_{is}^{-1}, \tag{2.4}$$

where

$$P_{ijs} = \left[\int_0^{N_{ijs}} p_{ijs}(\omega)^{1-\varepsilon_s} d\omega \right]^{\frac{1}{1-\varepsilon_s}}, \quad P_{is} = \left[\sum_{j=1}^{J} P_{ijs}^{1-\varepsilon_s} \right]^{\frac{1}{1-\varepsilon_s}}. \tag{2.5}$$

Firms In each sector, a fixed number of firms operate under monopolistic competition. Production decisions are taken separately across markets.[3] Production y_{ijs} of a firm located in j for location i in sector s is given by

$$y_{ijs} = \phi_{ijs} \left(\frac{z_{ijs}}{\beta_s} \right)^{\beta_s} \left(\frac{l_{ijs}}{\alpha_s} \right)^{\alpha_s},$$

where z_{ijs} is the energy use associated with the production, l_{ijs} is a composite physical input (factors other than energy), ϕ_{ijs} is a productivity shifter and α_s, β_s denote the output elasticities of physical inputs and energy. Sectors with decreasing returns-to-scale (DRS; $\alpha_s + \beta_s < 1$) exhibit an upward-sloping supply curve, whereas that curve is horizontal for sectors with constant returns (CRS; $\alpha_s + \beta_s = 1$).[4] The associated marginal cost function is given by

$$MC_{ijs} = \left(\frac{y_{ijs}}{\phi_{ijs}} \right)^{\gamma_s} p_{Zj}^{\beta_s(\gamma_s+1)} \phi_{ijs}^{-1},$$

where $\gamma_s \equiv \frac{1}{\alpha_s+\beta_s} - 1$ ($\gamma_s = 0$ implies CRS and $\gamma_s > 0$ implies DRS). p_{Zj} is the (exogenous) price of energy in country j.[5] The price of the composite physical input has been normalized to unity due to the presence of a freely traded outside good with a linear production function which uses the physical factor as the only input.

Energy use generates emissions in proportion to the prevailing share of fossil fuels in a country's energy mix. Emissions embedded in goods produced by j for i can be computed as

$$e_{ijs} = d_j z_{ijs},$$

where d_j denotes the rate of carbon emissions per unit of energy in country j.[6] Emission intensity of exports from j to i in sector s is given by:

$$\frac{e_{ijs}(p_{Zj}, y_{ijs})}{y_{ijs}} = d_j \beta_s y_{ijs}^{\gamma_s} p_{Zj}^{-\alpha_s(1+\gamma_s)} \phi_{ijs}^{-(1+\gamma_s)}, \tag{2.6}$$

[3] Separability of production decisions is realistic since most exporters are multi-plant firms that can operate plant-specific technologies with a different energy mix. Chen et al. (2025) show that Chinese multi-plant firms shift emissions between plants.

[4] Allowing for increasing returns ($\alpha_s + \beta_s > 1$) would be straightforward but our empirical estimates do not support this case.

[5] Exogenous energy prices rule out energy price leakage, i.e., additional demand for fossil fuels in non-EU countries which results from prices falling due to carbon taxation in the EU. This assumption is made in much of the CBAM literature (Böhringer et al., 2022) and relaxed in Sogalla (2023).

[6] Consistent with our focus on short-run analysis, we assume that d_j is fixed and does not respond to carbon pricing. In the longer run, the energy sector might adjust to higher prices of ETS allowances and CBAM certificates by investing in renewable electricity generation and other technologies that reduce d_j.

which is decreasing in p_{Zj} and increasing in y_{ijs} for $\gamma_s > 0$. Thus, the emission intensity of production may vary across countries due to variation in output, energy prices, or productivity.

To specify the relationship between energy prices and carbon taxes, denote by $\tilde{p}_{Zj}$ the energy price in j net of carbon taxes. Assuming a per-unit tax of τ_{Ej} Dollars per ton of CO_2 emissions, we write the price of a unit of energy gross of the carbon tax as $p_{Zj} = \tilde{p}_{Zj} + d_j \tau_{Ej}$.[7] Thus, the carbon tax increases the price of energy more in countries with higher carbon emission intensity d_j.

We assume iceberg trade costs τ_{ijs} for shipping a variety from j to i. Tariffs on imports by i on origin j in sector s are denoted by τ_{Iijs}, taxes on exports levied by j on exports to i in sector s are denoted as τ_{Xijs}. We abstract from trade taxes and transport costs within the same country ($\tau_{iis} = \tau_{Iiis} = \tau_{Xiis} = 1 \; \forall i$).

Since firms are monopolists for their variety, they set a markup over their marginal cost. The consumer price of a sector-s variety produced in i and consumed in j is then

$$p_{jis} = \tau_{jis} \tau_{Ijis} \tau_{Xjis} \mu_s \left(\frac{y_{jis}}{\phi_{jis}} \right)^{\gamma_s} p_{Zi}^{\beta_s(\gamma_s+1)} \phi_{jis}{}^{-1}, \tag{2.7}$$

where $\mu_s = \frac{\varepsilon_s}{\varepsilon_s - 1}$ denotes the sectoral markup.

Total profits of sector s in i are given by

$$\Pi_{is} = \sum_{j=1}^{J} \Pi_{jis}, \tag{2.8}$$

where

$$\Pi_{jis} = N_{jis} \left[\mu_s - \frac{1}{1+\gamma_s} \right] \left(\frac{y_{jis}}{\phi_{jis}} \right)^{\gamma_s+1} p_{Zi}^{\beta_s(\gamma_s+1)} \tag{2.9}$$

are the profits that firms earn in each market j.

Equilibrium in Levels Imposing market clearing in each sector, i.e., $y_{ijs} = \tau_{ijs} c_{ijs}$ and using (2.2), (2.3), (2.4) and (2.7), we can find an expression for the equilibrium levels of y_{ijs} and p_{ijs}.

$$y_{ijs} = \left(\eta_{is} \tau_{ijs}^{1-\varepsilon_s} \right)^{\frac{1}{\gamma_s \varepsilon_s + 1}} \left(\phi_{ijs} p_{Zj}^{-\beta_s} \right)^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \left(\mu_s \tau_{Iijs} \tau_{Xijs} \right)^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} P_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}}, \tag{2.10}$$

$$p_{ijs} = \eta_{is}^{\frac{\gamma_s}{\gamma_s \varepsilon_s + 1}} \left(\tau_{ijs} \phi_{ijs}^{-1} p_{Zj}^{\beta_s} \right)^{\frac{\gamma_s + 1}{\gamma_s \varepsilon_s + 1}} \left(\mu_s \tau_{Iijs} \tau_{Xijs} \right)^{\frac{1}{\gamma_s \varepsilon_s + 1}} P_{is}^{\frac{\gamma_s(\varepsilon_s - 1)}{\gamma_s \varepsilon_s + 1}}, \tag{2.11}$$

$$P_{is}^{\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s \varepsilon_s + 1}} = \sum_{j=1}^{J} N_{ijs} \left(\eta_{is}^{\frac{\gamma_s}{\gamma_s \varepsilon_s + 1}} \left(\tau_{ijs} \phi_{ijs}^{-1} p_{Zj}^{\beta_s} \right)^{\frac{\gamma_s + 1}{\gamma_s \varepsilon_s + 1}} \left(\mu_s \tau_{Iijs} \tau_{Xijs} \right)^{\frac{1}{\gamma_s \varepsilon_s + 1}} \right)^{1-\varepsilon_s}. \tag{2.12}$$

Equilibrium in Changes We can then rewrite the equilibrium conditions in terms of gross changes in variables $\hat{X} = \frac{X'}{X}$ from the initial equilibrium value X to the new equilibrium value X'. This allows us to express changes in equilibrium outcomes as:

$$\hat{y}_{ijs} = \left(\hat{\phi}_{ijs} \hat{p}_{Zj}^{-\beta_s} \right)^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \left(\hat{\tau}_{Iijs} \hat{\tau}_{Xijs} \right)^{\frac{-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\varepsilon_s - 1}{\gamma_s \varepsilon_s + 1}}, \tag{2.13}$$

$$\hat{p}_{ijs} = \left(\hat{\phi}_{ijs}^{-1} \hat{p}_{Zj}^{\beta_s} \right)^{\frac{\gamma_s + 1}{\gamma_s \varepsilon_s + 1}} \left(\hat{\tau}_{Iijs} \hat{\tau}_{Xijs} \right)^{\frac{1}{\gamma_s \varepsilon_s + 1}} \hat{P}_{is}^{\frac{\gamma_s(\varepsilon_s - 1)}{\gamma_s \varepsilon_s + 1}}, \tag{2.14}$$

[7] All nominal variables in the model are in US Dollars.

where $\hat{p}_{Zj} = \frac{\tilde{p}_{Zj}+d_j\hat{\tau}_{Ej}\tau_{Ej}}{\tilde{p}_{Zj}+d_j\tau_{Ej}}$. Moreover, given that by (2.3) and (2.4) $P_{ijs}C_{ijs} = P_{ijs}^{1-\varepsilon_s}P_{is}^{1-\varepsilon_s}$ and $P_{is}C_{is} = \eta_{is}$, we rewrite condition (2.5) in changes as:

$$\hat{P}_{is}^{1-\varepsilon_s} = \sum_{j=1}^{J} \delta_{ijs}\hat{p}_{ijs}^{1-\varepsilon_s}, \tag{2.15}$$

where $\delta_{ijs} \equiv \frac{P_{ijs}C_{ijs}}{P_{is}C_{is}}$ is the expenditure share of i on goods imported from j. Substituting (2.14) into (2.15) we obtain:

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \sum_{j=1}^{J} \delta_{ijs}(\hat{\phi}_{ijs}^{-1}\hat{p}_{Zj}^{\beta_s})^{\frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}}(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs})^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}. \tag{2.16}$$

This expression gives an explicit solution for the change in the price index. By combining (2.16) with (2.13) and (2.14) we can recover equilibrium changes in $\hat{y}_{ijs}$, $\hat{p}_{ijs}$, $\hat{c}_{ijs}$ and $\hat{C}_{ijs}$ as a function of changes in policy instruments, productivity shocks, parameters (β_s, γ_s, ε_s) and observable trade shares only. Finally, from (2.6) changes in emissions are given by

$$\hat{e}_{ijs} = \left(\frac{\hat{y}_{ijs}}{\hat{p}_{Zj}^{\alpha_s}}\right)^{1+\gamma_s}\hat{\phi}_{ijs}^{-(1+\gamma_s)} = \hat{y}_{ijs}^{1+\gamma_s}\hat{p}_{Zj}^{\beta_s(1+\gamma_s)-1}\hat{\phi}_{ijs}^{-(1+\gamma_s)}. \tag{2.17}$$

Welfare Welfare is given by

$$\begin{aligned} W_i &= C_{i0} + \int_s \eta_{is}\log C_{is}d_s - \theta_i\int_s e_s ds \\ &= I_i + \int_s \eta_{is}\log C_{is}d_s - \int_s P_{is}C_{is}ds - \theta_i\int_s e_s ds, \end{aligned}$$

where income $I_i = w_iL_i + \int_s \Pi_{is}ds + \int_s T_{is}d_s$ is derived from labor, profits and transfers. Worldwide emissions are given by $e_s \equiv \sum_{i=1}^{J}\sum_{j=1}^{J} N_{ijs}e_{ijs}$. Thus, welfare corresponds to consumer surplus, producer surplus, labor income, tax income, and the disutility from global emissions.

We compute the absolute difference in welfare before and after the policy change,

$$\begin{aligned} &W_i' - W_i \\ &= \int_s(\hat{\Pi}_{is}-1)\Pi_{is}ds + \int_s(\hat{T}_{is}-1)T_{is}ds + \int_s \eta_{is}\log\hat{C}_{is}ds - \theta_i\int_s(\hat{e}_s-1)e_s ds, \end{aligned}$$

where we have used the fact that $\widehat{P_{is}C_{is}} = 1$ from (2.4). We substitute $\hat{C}_{is} = \hat{P}_{is}^{-1}$ from the previous section and express $\hat{\Pi}_{is}$, Π_{is}, $\hat{T}_{is}$, and T_{is} in terms of observables (see Appendix B. 1.2). With quasi-linear utility, the marginal utility of income is unity. Thus, taking the outside good as the numéraire and defining it as money, changes in indirect utility correspond to the amount of money consumers need to receive/pay in order to stay indifferent to a policy change.

Changes in global emissions can be written as

$$\hat{e}_s = \sum_{i=1}^{J}\sum_{j=1}^{J}\hat{e}_{jis}\frac{N_{jis}e_{jis}}{\sum_{i=1}^{J}\sum_{j=1}^{J}N_{jis}e_{jis}}. \tag{2.18}$$

Using (2.6), (2.7), and (2.17), we obtain

$$e_s = \beta_s \mu_s^{-1} \sum_{i=1}^{J} p_{Zi}^{-1} d_i \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis},$$

and

$$\hat{e}_s = \sum_{i=1}^{J} \hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1} \sum_{j=1}^{J} \tilde{\sigma}_{jis} \left(\frac{\hat{y}_{jis}}{\hat{\phi}_{jis}} \right)^{(1+\gamma_s)}, \tag{2.19}$$

where $\tilde{\sigma}_{jis} = \frac{p_{Zi}^{-1} d_i \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}}{\sum_{i=1}^{J} p_{Zi}^{-1} d_i \sum_{j=1}^{J} \tau_{Ijis}^{-1} \tau_{Xjis}^{-1} \eta_{js} \delta_{jis}}$ are the global sales shares in each market, measured before trade and carbon taxes are applied.

2.3.2 Border Adjustment Mechanisms

This section characterizes the workings of various BAMs using the equilibrium-in-changes notation introduced above. All scenarios assume that country i unilaterally raises its domestic carbon tax ($\hat{\tau}_{Ei} > 1$) and that climate and trade policies remain unchanged in all other countries ($\hat{\tau}_{Ej} = \hat{\tau}_{Ijis} = \hat{\tau}_{Xijs} = 1$ for all $j \neq i$). Since we focus on the impact of policy changes, for simplicity, we assume that productivity shocks are absent ($\hat{\phi}_{ijs} = 1$ for all i, j, s). We comment on the effect of such shocks where appropriate.

No-BAM The unilateral carbon tax increase raises energy prices in the domestic market ($\hat{p}_{Zi} > 1$) while leaving foreign energy prices unchanged ($\hat{p}_{Zj} = 1$ for all $j \neq i$). In the absence of a BAM ($\hat{\tau}_{Iijs} = \hat{\tau}_{Xijs} = 1$ for all s and j), this puts domestic producers at a competitive disadvantage on the domestic and export markets. By combining (2.13) with (2.16), we obtain the equilibrium response in sales of domestic producers in their home market

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s \, (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} = \hat{p}_{Zi}^{\frac{-\beta_s \, (1+\gamma_s)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \left[\delta_{iis} \hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1 - \delta_{iis} \right]^{\frac{-1}{1+\gamma_s}} < 1$$

and imports from foreign producers in that market

$$\hat{y}_{ijs} = \hat{P}_{is}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} = \left[\delta_{iis} \hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1 - \delta_{iis} \right]^{\frac{-1}{1+\gamma_s}} > 1. \tag{2.20}$$

Intuitively, raising the domestic carbon tax raises the price of domestic relative to foreign varieties and leads to substitution of domestic consumption towards imported varieties. To the extent that domestic production is cleaner than abroad, this process increases global emissions as domestic output is replaced by more polluting foreign production (*import leakage*).

From (2.13) and (2.15) we obtain that the carbon-tax increase reduces exports:

$$\hat{y}_{jis} = \hat{p}_{Zi}^{\frac{-\beta_s \, (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \hat{P}_{js}^{\frac{\varepsilon_s-1}{1+\varepsilon_s\gamma_s}} = \hat{p}_{Zi}^{\frac{-\beta_s \, (\gamma_s+1)\varepsilon_s}{1+\varepsilon_s\gamma_s}} \left[\delta_{jis} \hat{p}_{Zi}^{\frac{\beta_s(1+\gamma_s)(1-\varepsilon_s)}{1+\varepsilon_s\gamma_s}} + 1 - \delta_{jis} \right]^{\frac{-1}{1+\gamma_s}} < 1.$$

The reduction in domestic exports increases global emissions as long as domestic production is cleaner than abroad (*export leakage*).

CBAM To level the playing field w.r.t carbon pricing, country i levies a tariff $\hat{\tau}_{Iijs}$ on imports from j in sector s such that import-embedded emissions are taxed at the same rate as domestic carbon emissions. CBAM thus requires knowledge of the carbon intensity of foreign production. We assume that this can be perfectly observed (having duly noted the importance of asymmetric information above).

CBAM raises the effective energy price for goods produced in j and exported to i, p_{Zij}, by an amount consistent with the domestic carbon tax, $\hat{p}_{Zij} = 1 + \frac{d_j \hat{\tau}_{Ei} \tau_{Ei}}{p_{Zj}} > 1$, assuming zero initial carbon prices in foreign countries ($\tau_{Ej} = 0$). For sectors s not affected by CBAM, energy costs remain unchanged ($\hat{p}_{Zij} = 1$).

In our model, the carbon tariff can be implemented by setting bilateral discriminatory tariffs equal to the cost pass-through of a carbon tax on imports, i.e., $\hat{\tau}_{Iijs} = \hat{p}_{Zij}^{\beta_s(\gamma_s+1)}$ in CBAM sectors and $\hat{\tau}_{Iijs} = 1$ elsewhere. Other trade instruments are not used ($\hat{\tau}_{Xijs} = 1$ for all $\forall s, j$). Using these assumptions in (2.13), (2.14), and (2.16), we obtain the following equilibrium responses to raising the domestic carbon tax in combination with CBAM tariffs:

$$
\begin{aligned}
\hat{y}_{ijs} &= \hat{p}_{Zij}^{\frac{-\beta_s(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}}, \\
\hat{p}_{ijs} &= \hat{p}_{Zij}^{\frac{\beta_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\gamma_s(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}, \\
\hat{P}_{is} &= \left[\sum_{j=1}^{J} \delta_{ijs} \hat{p}_{Zij}^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right]^{-\frac{\gamma_s\varepsilon_s+1}{(1+\gamma_s)(\varepsilon_s-1)}} > 1.
\end{aligned}
$$

Prices of all varieties rise, inducing $\hat{P}_{is} > 1$, and so do energy prices p_{Zij}, especially for varieties produced in locations with a carbon-intensive energy mix. However, in most cases this effect dominates and $\hat{y}_{ijs} < 1$. Since CBAM only applies to imports, there is export leakage as in No-BAM.

LBAM To prevent import leakage, country i introduces a tariff that stabilizes bilateral imports within each sector at the level before the carbon-tax increase. Consistent with this objective, domestic tariff changes $\hat{\tau}_{Iijs} > 1$ neutralize the effects on demand of imported varieties induced by $\hat{\tau}_{Ei} > 1$, in the sense that $\hat{C}_{ijs} = \hat{c}_{ijs} = \hat{y}_{ijs} = 1$ for all j and s. Imposing this condition on (2.13) and (2.16) yields[8]

$$
\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \delta_{iis} \hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + (1-\delta_{iis}) \hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \tag{2.21}
$$

with $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}\ \forall j$, i.e., LBAM tariffs are independent of the trade partner and hence non-discriminatory. Condition (2.21) implicitly defines a tariff that stabilizes bilateral imports for a change in the carbon tax $\hat{\tau}_{Ei}$ and the energy price $\hat{p}_{Zi}$. The tariff depends on (i) the effect of the carbon tax on the price of domestically produced varieties and (ii) on the effect of the tariff on the price of imported varieties from other countries, weighted by the respective expenditure shares. Computing the LBAM tariff only requires information on the elasticities of import demand ε_s and export supply γ_s, the output elasticity of emissions β_s, and the share of domestic absorption that falls on domestically produced varieties *before* the carbon tax increase δ_{ii}. Since the tariff holds the level of bilateral imports constant, the foreign

[8] In the appendix, we prove that any tariff that (i) prevents import leakage by keeping *aggregate* imports constant and (ii) does not discriminate between partner countries must hold *bilateral* imports from each origin country constant.

carbon intensity does not change, and hence import-embedded emissions also remain constant: LBAM prevents import leakage.

Observe that the formula for LBAM tariffs is independent of productivity shocks as long as such shocks are sector-specific, i.e., when $\phi_{ijs} = \phi_{is}$. In the more general case where productivity shocks are sector-country-specific, LBAM tariffs remain independent of these shocks up to a first-order approximation.[9] Thus, policy makers can disregard the effect of domestic or foreign productivity shocks when sterilizing the effect of domestic carbon price changes on imports. Instead, imports will fluctuate in response to domestic or foreign productivity shocks.

Combining (2.13) and (2.16) and imposing LBAM yields

$$\hat{y}_{iis} = \hat{p}_{Zi}^{\frac{-\beta_s \varepsilon_s (1+\gamma_s)}{1+\varepsilon_s \gamma_s}} \hat{\tau}_{Iis}^{\frac{\varepsilon_s}{1+\varepsilon_s \gamma_s}} < 1. \tag{2.22}$$

Thus, domestic sales to the home market fall, but by less than under the No-BAM scenario. Given that $\hat{\tau}_{Xjis} = 1$ for all $\forall j, s$, export leakage is the same as in the No-BAM scenario.

LBAM-X To prevent export leakage, country i introduces an export subsidy that keeps its bilateral exports within each sector constant at the level before the carbon-tax increase.[10] Formally, the export subsidy $\hat{\tau}_{Xjis} < 1$ is chosen such that $\hat{C}_{jis} = \hat{c}_{jis} = \hat{y}_{jis} = 1$ for all j, s, in response to $\hat{\tau}_{Ei} > 1$. Combining the last condition with (2.13) and (2.16) yields:

$$\hat{\tau}_{Xjis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s \varepsilon_s + 1}} = \delta_{jis} \hat{p}_{Zi}^{\beta_s(\gamma_s+1)} \hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s \varepsilon_s + 1}} + (1 - \delta_{jis}) \hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)^2 \varepsilon_s}{\gamma_s \varepsilon_s + 1}}. \tag{2.23}$$

A straightforward solution to this equation is a non-discriminatory export subsidy

$$\hat{\tau}_{Xi} = \frac{1}{\hat{p}_{Zi}^{\beta_s(\gamma_s+1)}}.$$

This subsidy exactly offsets the pass-through of higher energy prices (in the denominator) and thus prevents export prices from increasing, irrespective of the destination. Since the price index does not change ($\hat{P}_{js} = 1$), domestic producers do not change their exports ($\hat{y}_{jis} = 1$). The only information required to compute the LBAM-X export subsidy is the output elasticity of carbon β_s and the export supply elasticity γ_s. Finally, note that LBAM-X export subsidies are independent of domestic or foreign productivity shocks and do not interfere with them: exports will fluctuate freely in the presence of such shocks.[11]

[9] See Appendix B. 1.3.

[10] There is no connection between export and import decisions in the model, so the export border adjustment can be analyzed independently from import border adjustment.

[11] See Appendix B. 1.3.

2.3.3 Decomposition of Emissions Changes

To clarify how global emissions and carbon leakage are affected by climate and trade policies, we decompose equation (2.19) as follows:

$$\hat{e}_s = \underbrace{\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\tilde{\sigma}_{iis}\hat{y}_{iis}^{1+\gamma_s}}_{\substack{\textbf{(i)}\ \textit{Emission changes due to}\\ \textit{a change in production of domestically}\\ \textit{consumed and produced goods}}} + \underbrace{\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\sum_{j\neq i}^{J}\tilde{\sigma}_{jis}\hat{y}_{jis}^{1+\gamma_s}}_{\substack{\textbf{(ii)}\ \textit{Emission changes due to}\\ \textit{changes in domestic exports}}} \tag{2.24}$$

$$+ \underbrace{\sum_{j\neq i}^{J}\tilde{\sigma}_{ijs}\hat{p}_{Zj}^{\beta_s(1+\gamma_s)-1}\hat{y}_{ijs}^{1+\gamma_s}}_{\substack{\textbf{(iii)}\ \textit{Emission changes due to}\\ \textit{changes in domestic imports}}} + \underbrace{\sum_{k\neq i}^{J}\sum_{j\neq i}^{J}\tilde{\sigma}_{jks}\hat{y}_{jks}^{1+\gamma_s}}_{\substack{\textbf{(iv)}\ \textit{Emission changes due to}\\ \textit{changes in production of goods consumed}\\ \textit{and produced in the rest of the world}}}.$$

The four components disentangle equilibrium changes in domestic emissions from those in foreign emissions.

Emissions embedded in domestic production By increasing the cost of energy inputs, a rise in the domestic carbon tax directly reduces the emissions embedded in each unit of domestic production. Moreover, since production for the home market falls in response to a domestic carbon-tax increase ($\hat{y}_{iis} < 1$), so do emissions (i). The same mechanism reduces domestic emissions from exports ($\hat{y}_{jis} < 1$) unless an LBAM-X export subsidy is granted (ii).

Import leakage In the absence of import-related BAMs, emissions embedded in imports increase in response to a carbon-tax increase (iii). LBAM tariffs completely sterilize such import leakage by ensuring $\hat{y}_{ijs} = 1$. In contrast, the effect of CBAM on leakage depends very much on how it is implemented, as we will show below.

Export leakage Since prices of domestic exports increase with the carbon tax, foreign consumers substitute towards varieties produced in third countries. This increases output in those countries and thus leads to higher emissions in the rest of the world rise (iv). LBAM-X export subsidies can prevent export leakage.

2.4 Calibration

We calibrate the model for the EU-27 and 56 other countries, using data on 131 4-digit manufacturing industries from the year 2018. Sector-level price elasticities of import demand and export supply are estimated on bilateral trade flows for these countries using state-of-the-art methods (Broda and Weinstein, 2006; Feenstra, 1994; Soderbery, 2015). Sectoral output elasticities of energy and physical production factors are obtained by estimating sector-specific production functions on firm-level data from the German manufacturing census (Ackerberg et al., 2015; Wooldridge, 2009). We analytically solve for an initial equilibrium with a low carbon price of $15 (the average EU-ETS price in 2018) and one with a high carbon price of $105 per ton (the approximate average price in 2023). We assume an SCC of $178 per ton of CO_2 equivalent, based on the central estimate in Rennert et al. (2022), discounted back to 2018. Equilibrium objects that depend on unknown parameters are replaced with data on bilateral trade flows and absorption (Dekle et al., 2007; Ossa, 2014). To estimate foreign emissions intensities, we use our model in combination with newly compiled data on industrial energy prices and fuel mixes across countries. The remainder of this section describes the data and parameter estimation in more detail.

2.4.1 Data

A realistic calibration of the model calls for detailed data that we compile from a host of sources. First, we need sectoral production and trade data for all countries in the sample for the year 2018 to construct the sectoral expenditure η_{is} and bilateral expenditure shares δ_{ijs}. We obtain 4-digit production (gross output) data for each country from UNIDO INDSTAT 2022 at the ISIC Rev. 4. level. For EU-27 and other European countries, we compile these data from Eurostat's COMEXT database and convert it from NACE Rev. 2 to ISIC Rev. 4 classification.

Second, we source bilateral product-level import and export values at the 4-digit ISIC Rev. 3 level from the World Integrated Trade Solution (WITS) and convert them to the ISIC Rev. 4 classification. Sectoral expenditure η_{is} is defined as absorption (i.e., production minus total exports plus total imports) and expenditure shares are computed as the share of bilateral sectoral imports in total sectoral expenditure.

Third, we need bilateral sectoral tariff data for 2018 to compute the initial tariffs τ_{Iijs}. We source bilateral applied tariff rates at the 4-digit ISIC Rev. 3 level from WITS and convert them to ISIC Rev. 4.[12] We set the initial levels of gross export taxes τ_{Xij} to unity because there is no systematic data on export taxes, and because export subsidies are forbidden under WTO rules.

Fourth, we need data for the carbon emission intensity of energy d_i by country. We source information on energy use in manufacturing by fuel type (coal, oil, natural gas, electricity) for the year 2018 from the International Energy Agency (IEA World Energy Statistics-World Energy Balances).[13] The country-specific emission intensity parameter d_i is computed as a weighted average of energy use by fuel type using emission factors from the Intergovernmental Panel on Climate Change (IPCC 2006 emission factor database for manufacturing industries). To gauge the carbon intensity of the electricity sector in each country, we use data on total CO_2 emissions and total generation of the electricity sector from IEA (IEA World CO_2 Emissions from Fuel Combustion). More details are provided in the Appendix.

Fifth, given the prominent role of energy prices in the model, we go to great lengths compiling data on energy prices p_{Zi} in US$/ton or US$/MWh for 2018 from a host of sources, including the IEA World Energy Prices, World Energy Prices Yearly, Enerdata, and GlobalPetrolPrices.com. Whenever information is missing in these data sources, we complement it with information from other sources, such as national statistics. As a last resort, when no such information is available for a given country, we impute values based on predictions from an OLS regression of (log) energy prices on region dummies, producer dummies, GDP per capita, population, and capital stock, which we obtain from Penn World Tables 9.0 and BP Statistical Review of World Energy. Oil and coal prices are converted from US$/ton to US$/TJ using conversion factors from the UN Statistics Division, 2004 Energy Balances and Electricity Profiles.

[12] The original data source in WITS is TRAINS at the HS6 level.

[13] Where information is missing, we impute fuel consumption with a regression on country-level correlates of energy use (GDP per capita, population, capital intensity, obtained from Penn World Tables 9.0) and region dummies.

The result is a comprehensive dataset of the energy mix among industrial firms and the fuel prices they pay across countries. With this in hand, we compute the country-specific energy price index p_{Zi} as the average energy price weighted by the fuel shares. More details are provided in the Appendix.

2.4.2 Demand Elasticities and Returns to Scale

Demand elasticities ϵ_s and returns to scale γ_s play a key role in our model. To estimate these parameters, we follow the methodology developed by Feenstra (1994), Broda and Weinstein (2006) and, in particular, Soderbery (2015). Rewriting the demand equation (2.3) in terms of market shares $\delta_{ijs} \equiv \frac{P_{ijs}C_{ijs}}{P_{is}C_{is}}$ yields

$$\log \delta_{ijst} = (1-\varepsilon_s)\log P_{ijst} + (\varepsilon_s - 1)\log P_{ist}.$$

To facilitate consistent estimation, we first eliminate origin-sector-specific unobservables by taking time differences of log prices and log market shares (denote first differences by Δ). Second, to eliminate sector-importer-time specific unobservables, such as the price index in the importing country, P_{ist}, we difference again by a reference country k (denote reference differences by superscript k). Write the double-differenced demand equation as

$$\Delta^k \ln \delta_{ijst} = \Delta \log \delta_{ijst} - \Delta \log \delta_{ikst} = (1-\varepsilon_s)\Delta^k \log p_{ijst} + \epsilon^k_{ijst}, \tag{2.25}$$

where ϵ^k_{ijst} are unobservable demand shocks.[14]

To derive the empirical analog of the supply equation (2.7), we write the price of a country-j, sector-s firm in market i as a function of the market share

$$p_{ijst}^{1+\gamma_s} = \left(\mu_s \tau_{ijs}\tau_{Iijs}\tau_{Xijs} p_{Zj}^{\beta_s(\gamma_s+1)} \phi_{ijst}^{-(1+\gamma_s)}\right)(\delta_{ijst}\eta_{ist})^{\gamma_s}$$

.

Taking logs and assuming that the tax instruments are constant over time, the double-differenced supply equation can be written as:

$$\Delta^k \log P_{ijst} = \Delta \log P_{ijst} - \Delta \log P_{ikst} = \frac{\gamma_s}{1+\gamma_s}\Delta^k \log \delta_{ijst} + \omega^k_{ijst}, \tag{2.26}$$

where $\omega^k_{ijst} = -\Delta^k \log(\phi_{ijst})$ are unobservable supply shocks.

The estimator relies on a variance identification and, in particular, the assumption that supply and demand shocks are orthogonal, i.e. $\mathbb{E}(\epsilon^k_{ijst}\omega^k_{ijst}) = 0$. The sample analog of this condition leads to an estimation equation for σ_s and γ_s (Feenstra, 1994) which we estimate using the hybrid limited information maximum likelihood estimator developed by Soderbery (2015).

We estimate demand and supply elasticities at the 4-digit level from EU import data.[15] Table 2.1 reports summary statistics for our estimates of demand and supply elasticities, which are similar to those reported by Soderbery (2015). Our mean demand elasticity is 4.6 and the

[14]Note that the term $1/(\varepsilon_s - 1)\log N_{ijs}$ does not vary over time and thus drops from the equation when taking time differences.

[15]We use data on the EU's bilateral import values and quantities from EUROSTAT for the sample period 2005-2018 at the 8-digit NACE level (Extrastat) and 4-digit NACE production data, which we convert both to the ISIC Rev.2 4-digit sector level. We construct import prices by dividing unit values by import quantities and market shares by dividing bilateral import values by the EU's total imports.

median is 2.4. Our median estimate for γ_s is 0.5, implying that the typical sector exhibits decreasing returns to scale ($\alpha_s + \beta_s = 0.67$). In Section 2.6, we show that our results are qualitatively robust to setting $\gamma_s = 0$ (CRS) and $\epsilon_s = 6$ for all sectors, which have been suggested as standard values in the literature (Costinot and Rodríguez-Clare, 2014).

2.4.3 Output Elasticities

Production of gross output in 4-digit industries resorts to labor, capital, materials, and energy inputs. In the absence of a European-wide dataset on firm-level energy use (Wagner et al., 2020), we use restricted-access data from the annual census of German manufacturing industries (AFiD- *Amtliche Firmendaten in Deutschland*). German AFiD data combine broad industry coverage with high representativeness. As demonstrated by earlier work, AFiD data are highly suitable for analyzing how energy inputs and CO_2 emissions interact with other input factors in the production process (Gerster and Lamp, 2024; Petrick et al., 2011).

AFiD covers the universe of German manufacturing plants with more than 20 employees, corresponding to approximately 50,000 plants per year. We construct a representative panel of firms for the years from 1998 until 2018 with information on electricity consumption and primary energy use by fuel type, gross output, employment, allowance for depreciation, and materials (drawn from AFiD modules *Energieverbrauch, Industriebetriebe* and *Industrieunternehmen*). We back out firm-level capital stocks by combining firm-level depreciation of fixed assets with sector-level averages of the lifetime of fixed assets, following Wagner (2010).

For each 4-digit NACE industry, we estimate a gross-output production function which is Cobb-Douglas in the factors capital, number of workers, materials, and energy. To address well-known endogeneity issues, we adopt the estimator by Wooldridge (2009), using either materials or energy as proxy variables and instrumenting for endogenous inputs with their first and/or second lags. The estimator employs the moment conditions proposed by Olley and Pakes (1996) and Levinsohn and Petrin (2003) in a joint GMM framework that addresses the critique by Ackerberg et al. (2015) by placing additional restrictions on the underlying data-generating process. This is slightly less general than their solution but offers computational benefits which are essential in the remote-server environment that governs our data access at the German Federal Research Data Centre.

Following the estimation, we retain the output elasticity of energy, β_s, and aggregate all non-energy elasticities to obtain the elasticity of the composite physical input, α_s. Finally, we convert the estimates to the ISIC Rev.4 classification.[16] We rescale output elasticities to make them compatible with the returns to scale estimate obtained from the trade data above. Table 2.1 reports summary statistics of the production function coefficients. The median output to energy elasticity is 0.06, while the median output elasticity to the composite physical input equals 0.53. We provide robustness checks for these estimates in section 2.6.

2.5 Policy Scenarios and Results

We quantify the impact of an increase in the EU carbon price from \$15 to \$105 on global emissions, bilateral trade flows between the EU and third countries, EU money-metric welfare, the distribution of abatement across sectors, and the economic costs imposed on non-EU

[16] To obtain a single output elasticity per ISIC industry, we take an unweighted average of all elasticities with non-negative coefficients after removing obvious outliers. To implement this, we construct a crosswalk between NACE Rev. 2 and ISIC Rev. 4. For those 4-digit industries for which we are not able to obtain a meaningful output elasticity estimate in this way, we use two-digit industry output elasticities.

Table 2.1: Summary Statistics of Production Function Parameters and Demand Elasticities

	No. Obs.	Mean	Median	Min	Max	SD
α_s	131	0.541	0.530	0.061	0.993	0.306
β_s	131	0.086	0.063	0.001	0.393	0.085
γ_s	131	2.020	0.563	0.000	10.045	3.171
ε_s	131	4.613	2.415	1.317	18.078	5.124

Notes: Summary statistics of GMM estimates for sector-level estimates of demand and supply parameters.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2018, AFiD-Panel Industriebetriebe 1998–2018, AFiD-Panel Industrieunternehmen1998–2018, project-specific preparations, own calculations.

countries. Non-EU countries are assumed to keep their tax instruments unchanged. We consider the case of No-BAM, three CBAM variants, and two LBAM scenarios: CBAM-EU denotes the current implementation that applies only to aluminum, iron and steel, fertilizers, and cement. All other policies apply to all sectors. Specifically, CBAM-ID is the *ideal* variant that would tax import-embedded emissions across *all* sectors. CBAM-EZ is a simpler variant where embedded emissions are computed using EU (rather than foreign) carbon intensities. The LBAM scenario implements tariffs that eliminate import-related leakage in all sectors. LBAM-X additionally assumes that the EU grants export subsidies that sterilize export leakage.

EU TRADE Table 2.2 summarizes the changes in EU trade across policy scenarios. Without border adjustments, bilateral imports increase by 11% on average, and by up to 305% in some sectors (Panel A). This is because unilateral carbon pricing increases energy costs for EU producers and thereby shifts comparative advantage to dirty producers, inducing substantial import leakage. In contrast, CBAM-ID *reduces* imports compared to no carbon pricing by 8% on average, and virtually shuts down trade in some very carbon-intensive sector-country pairs.[17] CBAM-EU gives rise to both these phenomena; average imports increase by almost 10%, whereas imports for some sector-country-pairs drop by up to one half. As explained in Section 2, this is because the objective of CBAM tariffs is to tax emissions embedded in domestic consumption. This implies that, in most cases, tariffs reduce imports beyond what is needed to prevent carbon leakage, and provides a rationale for strong opposition by non-EU countries against CBAM as a policy that limits access to EU markets (WTO, 2024). LBAM avoids this by raising tariffs just enough to eliminate import leakage. Given high average trade elasticities, modest LBAM tariffs of 1.3% on average would suffice (median 0.6%, maximum 8.6%; Panel B). In contrast, implementing CBAM across all sectors would raise bilateral tariffs by 8.3% on average (7.5% in the EZ variant), and double tariff rates in some industries. While CBAM-EU leaves most imports untaxed, affected sectors will see tariff increases as high as 39.2%.

Unilateral carbon pricing weakens the competitiveness of EU exporters on world markets, reducing bilateral EU exports by 9.4% on average and almost 80% in the most impacted sector-country pairs (Panel C). Border adjustments on imports leave this export leakage intact.

[17] Conversely, EU imports of cleaner goods increase in a small number of country-sector pairs.

Table 2.2: Impact of EU Carbon Price Increase on EU Trade

Leakage Policy	**Mean**	**Median**	**SD**	**Min**	**Max**
A. Imports (% change)					
No-BAM	11	0	35	0	305
CBAM-EU	10	0	35	-51	305
CBAM-ID	-8	-3	21	-100	482
CBAM-EZ	-8	-3	17	-100	253
LBAM, LBAM-X	0	0	0	0	0
B. Import tariffs (% change)					
No-BAM	0	0	0	0	0
CBAM-EU	0.3	0	1.7	0	39.2
CBAM-ID	8.3	5.7	8.8	0	105.6
CBAM-EZ	7.5	5.3	7.8	0.1	94.8
LBAM, LBAM-X	1.3	0.6	1.8	0	8.6
C. Exports (% change)					
No-BAM, CBAM-**, LBAM	-9.4	-2.9	15.4	-79.5	-0.0
LBAM-X	0	0	0	0	0
D. Export subsidies (% change)					
No-BAM, CBAM-**, LBAM	0	0	0	0	0
LBAM-X	3.7	3.0	2.6	0.2	10.5

Notes: Summary statistics of changes in EU trade and trade policy relative to 2018, following an EU carbon price increase from $15 to $105 per ton. Statistics are reported for: imports (Panel A), import tariffs (Panel B), exports (Panel C), and export subsidies (Panel D).

However, it can be neutralized with a modest export subsidy under the LBAM-X scenario, which averages at 3.7% across sector-country pairs and never exceeds 10.5%. In Appendix Tables B.5 and B.6, we report changes in EU imports and exports aggregated by 2-digit sector for readability.[18] Imports surge in virtually all sectors due to the EU carbon price increase, while exports fall across the board. The magnitudes of these adjustments are very heterogeneous across sectors, as they are governed by a complex combination of factors, including trade elasticities, energy intensity, returns to scale, and size.

EU welfare and global emissions Table 2.3 compares the policy scenarios in terms of two outcomes: EU welfare effects, comprised of economic costs and environmental benefits, and impact on global emissions. Column (iv) shows that unilaterally increasing its carbon price has significant economic costs for the EU, but the incidence varies substantially across policies, as shown in columns (i)-(iii): No-BAM and CBAM-EU are practically indistinguishable in terms of economic costs and load the bulk of them on consumers, while profits fall moderately and government revenue surges. Compared to those scenarios, CBAM-ID and CBAM-EZ *halve* the economic costs as the boost in government revenue induced by taxing all import-

[18] Remember that the model simulations are disaggregated into 131 4-digit sectors. Aluminum, iron and steel fall into the sector Metals, while fertilizers are part of Chemicals and cement is part of Minerals.

Table 2.3: Impact of EU Carbon Price Increase on EU Welfare and Global Emissions

	(i) Government Revenue	(ii) Consumer Surplus	(iii) Profits	(iv) Economic Costs = (i)+(ii)+(iii)	(v) Environmental Benefit	(vi) Welfare = (iv) + (v)	(vii) Global Abatement [%]
No-BAM	68.6	-101.7	-23.6	-56.7	31.9	-24.9	0.85
CBAM-EU	70.4	-103.6	-22.7	-55.9	32.9	-23.0	0.87
CBAM-ID	135.5	-151.8	-8.8	-25.1	53.8	28.7	1.43
CBAM-EZ	129.2	-146.4	-10.1	-27.2	49.4	22.2	1.31
LBAM	79.1	-112.1	-18.7	-51.6	36.6	-15.1	0.97
LBAM-X	32.6	-112.1	27.3	-52.2	48.1	-4.1	1.28

Notes: Change in EU welfare (vi) and its components (i-iii, v) following an EU carbon price increase from $15 to $105, in billions of 2018 US$. The percentage reduction in global emissions (vii) is relative to 2018 levels and valued at a SCC of $178 per ton to compute the global environmental benefit (v, in billions of 2018 US$).

embedded carbon emissions (and, to a lesser extent, a smaller contraction in domestic profits) compensates for the (even larger) drop in consumer surplus.

After netting out environmental benefits, only the comprehensive CBAMs lead to welfare gains for the EU in the amount of $29 bn (CBAM-ID) and $22 bn (CBAM-EZ), reported in column (vi). In contrast, welfare losses are largest for No-BAM and for CBAM-EU ($25 bn and $23 bn, respectively).[19] LBAM policies outperform both CBAM-EU and No-BAM in terms of welfare because they generate significantly larger environmental benefits. Compared to the comprehensive CBAMs, they impose a smaller burden on EU consumers but also generate much less tariff revenue. LBAM gives rise to a welfare loss of $15.1 bn, a reduction by one third compared to CBAM-EU. Additionally subsidizing EU exports to prevent export leakage (LBAM-X) brings the welfare loss down to $4 bn as environmental benefits rise to a level comparable to the comprehensive CBAMs. LBAM-X also boosts profits by shifting government revenue to exporting firms in the EU.

Higher carbon taxes generate global environmental benefits in proportion to EU emissions reductions, net of carbon leakage arising from the trade impacts documented above. Comparing global abatement across scenarios, reported in column (vii) of Table 2.3, reveals the extent of carbon leakage. Since LBAM-X holds foreign production fixed at the level before the carbon price increase, global abatement in this scenario (1.28%) is entirely determined by how EU emitters respond to the increase in the EU-ETS price. Without any border adjustments, global abatement drops to 0.85%, implying that one out of three tons of CO_2 abated in the EU 'leaks' to the rest of the world. LBAM import tariffs prevent only 30% of such carbon leakage. The remaining 70% occur due to the substitution of EU exports with production from the rest of the world. Such export leakage is not mitigated by any policy except LBAM-X, as shown in Figure 2.2. Universal applications of CBAM achieve comparable reductions in world emissions but require larger reductions in domestic production and imports. This is because CBAM implements (CBAM-ID) or approximates (CBAM-EZ) a consumption-based carbon tax for the EU which discourages carbon-intensive production in the foreign export sectors. Due to its limited sector coverage, however, CBAM-EU reduces carbon leakage only minimally.

The result that comprehensive CBAMs impose the smallest economic cost on the EU is due to CBAM's extraterritorial effects and comes at the expense of the EU's trade partners whose exports contract in response to high EU carbon prices. On environmental grounds, shifting abatement towards non-EU countries is not strictly necessary; by shutting down import *and* export leakage, LBAM-X yields almost the same emissions reductions as the feasible consumption-based carbon tax CBAM-EZ.

Cross-sectoral abatement To shed light on the distribution of abatement across sectors, Appendix Table B.7 reports the percentage change in global emissions attributed to each 2-digit sector measured relative to global sectoral emission levels in 2018. Only in the metals sector does CBAM-EU increase the environmental effectiveness of EU carbon pricing

[19] Our calculations attribute the global environmental benefit entirely to the EU while setting $\theta_i = 0$ for non-EU countries. This parameterization closely aligns with the intention behind CBAM to support globally optimal emissions abatement by the EU when other countries do not value such abatement; it provides an upper-bound estimate of the welfare the EU can get by taking this unilateral approach. As an alternative, we assign a share of the global SCC to each country following the approach in Farrokhi and Lashkaripour (2025). This renders welfare changes more negative but leaves the ranking of policy instruments unchanged. This and other robustness checks are discussed in Section 2.6 below.

compared to No-BAM. In contrast, the more comprehensive border adjustment mechanisms lead to greater emissions reductions in virtually all sectors.

Third-country economic costs Figure 2.3 illustrates the economic costs of EU policies imposed on other countries in terms of their distribution across countries (2.3a) and their composition for the average country (2.3b).[20] In non-EU countries, higher export prices from the EU induce substitution to otherwise less competitive suppliers. Without BAM, or with CBAM-EU, this negative effect dominates the positive effect of increased competitiveness in most countries, imposing small costs. By contrast, the comprehensive CBAMs induce large additional economic costs on many non-EU countries as they significantly reduce exports to the EU (up to $20 bn. for China). Therefore, broadening CBAM's sector coverage in the future, as envisaged by the EU, will likely amplify the already strong political opposition from BRICS states and other countries towards this policy. This conclusion is robust to attributing a share of global environmental benefits to each country because the economic costs would still outweigh the environmental benefits in most countries (see Section 2.6 below).

Since LBAM neutralizes the (positive) effect on EU imports, many countries are left with economic costs that are a bit larger than under no-BAM. LBAM-X additionally restores EU exports to their initial levels, thus eliminating all economic impacts on foreign countries. Hence, LBAM-X avoids negative extraterritorial effects of EU climate policies while providing large global environmental benefits—a combination that would render it politically acceptable for all countries. The export subsidies we propose thus provide a valuable reference as the EU Commission is beginning the process of designing support measures that mitigate the risk of carbon leakage for EU-exporters of CBAM goods (European Commission, 2025).

2.6 Robustness

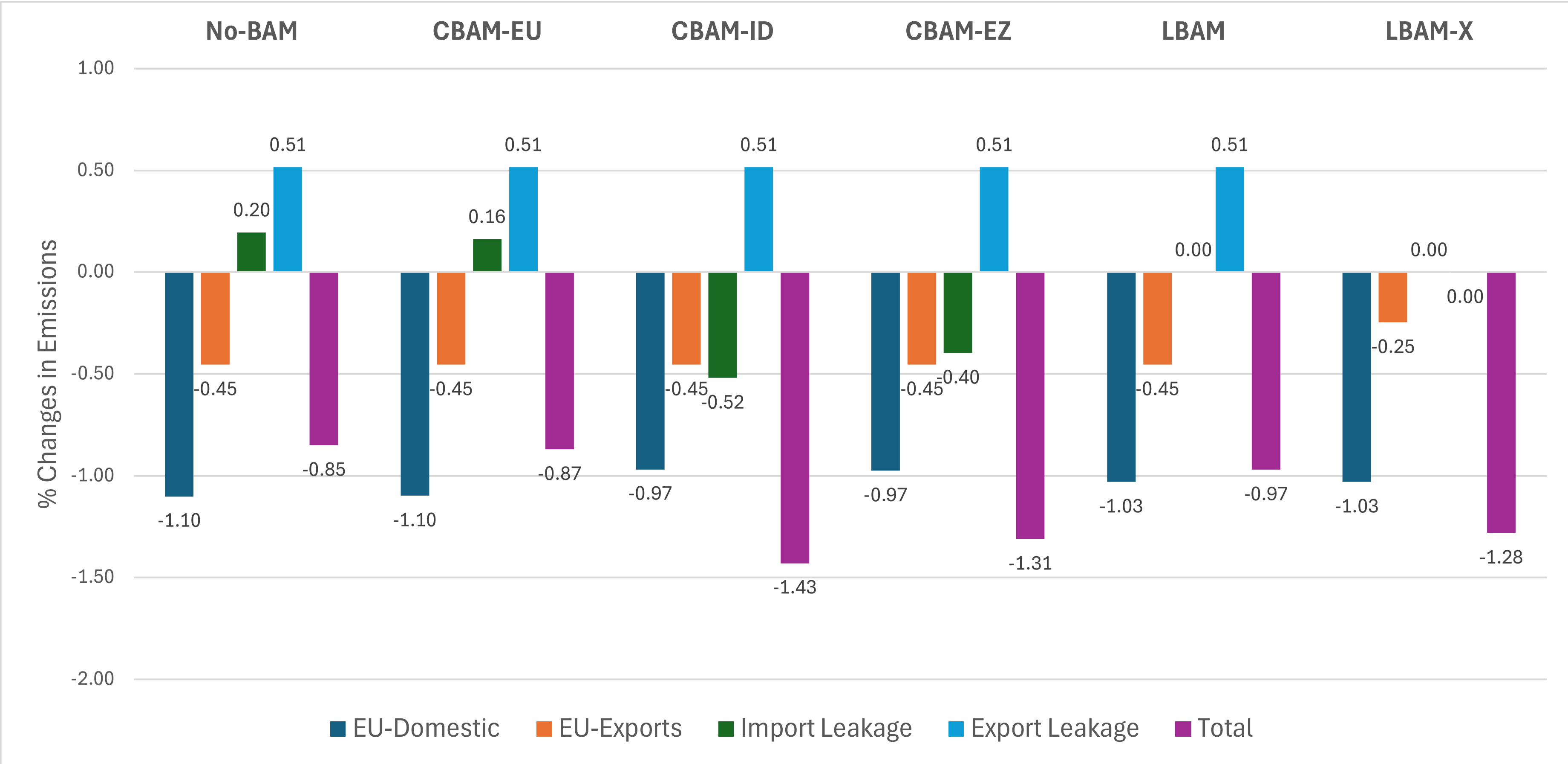
This section assesses the robustness of our results to using alternative values for some key parameters. We start by showing welfare results for the EU and Non-EU countries when assuming country-specific values for the social cost of carbon instead of attributing the global welfare benefit of abatement to the EU. We then discuss welfare and emission results obtained for alternative choices of the trade and output elasticities.

Country-level SCC Disaggregating global estimates of SCC down to the level of the individual country is methodologically challenging and subject to ongoing research. Here we adopt the approach proposed by Farrokhi and Lashkaripour (2025) who recover country-specific estimates of the disutility from emissions via a revealed preference approach, based on implemented environmental taxes scaled by population and energy use. The sum of these country-level disutilities is assumed to equal the global SCC.[21] Figure B.2 in the Appendix shows the SCC for selected countries.

[20]Notice that, under the baseline calibration, economic costs and welfare imposed on non-EU countries coincide.

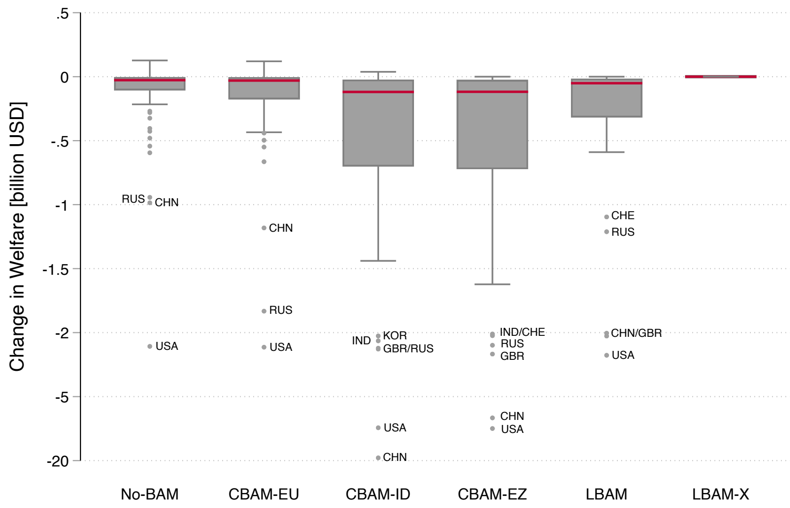
[21]To apply their estimates to our data, we first allocate the SCC to the countries in our sample, as our country coverage differs from theirs. Countries included in Farrokhi and Lashkaripour (2025)'s sample but not in ours, specifically Turkey and Japan, are excluded. We assign countries that are included in our sample but absent from theirs to the appropriate 'Rest-of-the-World' regions defined in their study and distribute the SCC according to population shares within each region. We also apply this approach to recover the SCC of the United Kingdom, initially part of the EU aggregate, but treated as a separate country following Brexit. Finally, we rescale the values so that the sum matches our preferred global SCC estimate of $178.

Figure 2.2: Impact of EU Carbon Price Increase on Carbon Emissions

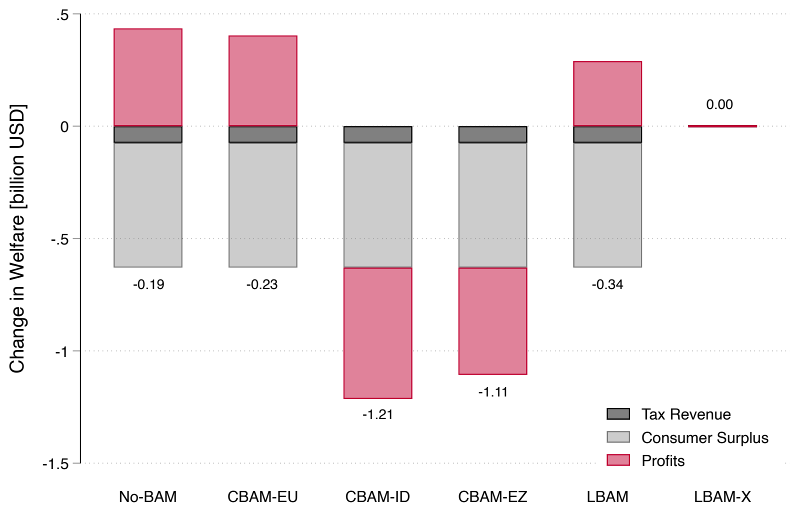


Notes: The figure shows the percentage change in emissions following a unilateral increase in the EU carbon price from \$15 to \$105 per ton. Emissions changes (in % of baseline emissions) are computed for six scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X. Following the decomposition in eq. (2.24), total emissions change due to changes in (i) EU production for the home market (EU-Domestic), (ii) EU production for the export market (EU-Exports), (iii) foreign production for the EU market (Import leakage), and (iv) foreign production for other foreign markets (Export leakage).

Figure 2.3: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries



(a) Distribution of the changes in economic costs



(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from \$15 to \$105 per ton. Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US\$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

Table 2.4: Impact of EU Carbon Price Increase on EU Welfare and Global Emissions for alternative choice of SCC

	(i) Government Revenue	(ii) Consumer Surplus	(iii) Profits	(iv) Economic Costs = (i)+(ii)+(iii)	(v) Environmental Benefit	(vi) Welfare = (iv) + (v)	(vii) Global Abatement [%]
No-BAM	68.6	-101.7	-23.6	-56.7	12.7	-44.0	0.85
CBAM-EU	70.4	-103.6	-22.7	-55.9	13.1	-42.8	0.87
CBAM-ID	135.5	-151.8	-8.8	-25.1	21.4	-3.7	1.43
CBAM-EZ	129.2	-146.4	-10.1	-27.2	19.7	-7.5	1.31
LBAM	79.1	-112.1	-18.7	-51.6	14.6	-37.1	0.97
LBAM-X	32.6	-112.1	27.3	-52.2	19.2	-33.0	1.28

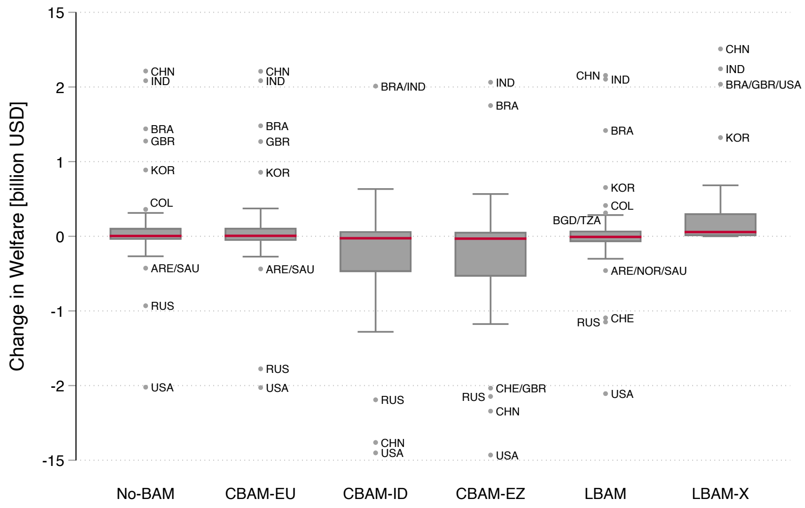
Notes: Change in EU welfare (vi) and its components (i-iii, v) following an EU carbon price increase from \$15 to \$105, in billions of 2018 US\$. The percentage reduction in global emissions (vii) is relative to 2018 levels and valued at a SCC of \$178 per ton to compute the global environmental benefit. Column (v) reports the EU's share in global environmental benefits (in billions of 2018 US\$) computed following Farrokhi and Lashkaripour (2025).

Table 2.4 reports the EU welfare effects when adopting country-specific SCC estimates. The EU's SCC is reduced from $178 to $71, which lowers the estimated environmental benefits by approximately 60%. As a result, the net welfare effect for the EU turns negative across all policy scenarios, including those that delivered a net welfare gain with our preferred parameterization (CBAM-ID and CBAM-EZ). The relative welfare ranking of scenarios is not affected, however: LBAM and LBAM-X still provide larger welfare than No-BAM or CBAM-EU.

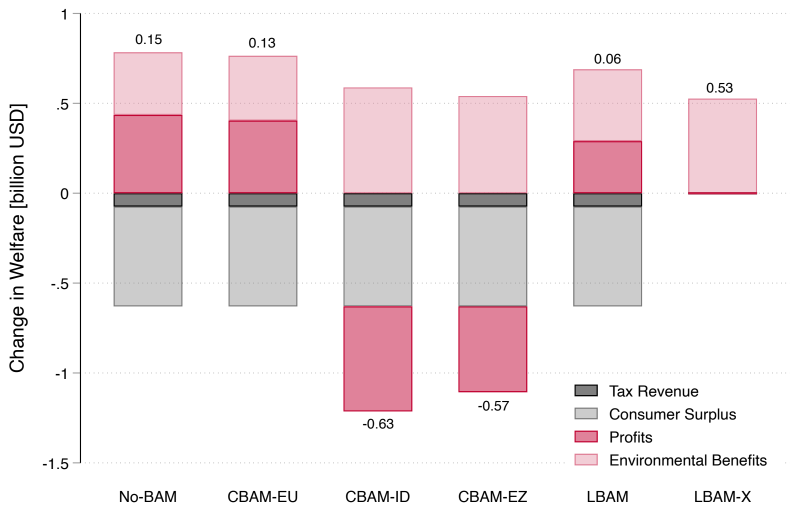
In contrast to the EU, non-EU countries benefit from assigning country-specific SCC estimates to them. Except under CBAM-ID and CBAM-EZ, welfare increases across these countries (see Figure 2.4b). However, CBAM-ID and CBAM-EZ, which achieve the largest emissions reductions relative to the benchmark still imply large welfare losses for many countries, in particular for the US and China (see Figure 2.4a). Under No-BAM, CBAM-EU or LBAM, countries either experience small welfare losses or small gains. LBAM-X makes all foreign countries better off as they now value global emission reductions while still facing zero economic costs.

Alternative trade and output elasticities We now turn to the robustness checks on the other structural model parameters. In our first robustness check, we exclude outliers from the data when computing trade and output elasticities. Rather than winsorizing, we impose a sensible upper bound on the output elasticity of energy to limit the influence of extreme values. Missing elasticity estimates are imputed using available 4-digit industry values within the same 2-digit classification. The same procedure is applied to trade elasticities. In the second robustness check, we compute capital stocks using the perpetual inventory method instead of using the method proposed by Wagner (2010). In the third robustness check, instead of using estimated values for the returns to scale and the trade elasticity for each sector, we set them to standard values in the literature. Specifically, we set $\gamma = 0$ (implying CRS) and $\varepsilon = 6$ (Costinot and Rodríguez-Clare, 2014) for all sectors. Appendix Table B.8 reports summary statistics of these alternative parameters. We report the EU welfare and global emission effects for these robustness checks in Table 2.5. In addition, Appendix Figures B.3- B.5b show box plots of the distribution of the foreign economic costs, as well as a decomposition of average foreign economic costs, respectively. Compared to the baseline calibration, the numbers change somewhat across the different robustness checks. However, the ranking of scenarios in terms of welfare and emissions reductions remains unchanged. Moreover, the distribution of economic costs also remains heterogeneous across countries, with the most impacted countries experiencing costs of EU policies of up to $ 15-20 bn.

Figure 2.4: Impact of EU Carbon Price Increase on Welfare for Non-EU Countries for alternative choice of SCC



(a) Distribution of the changes in welfare



(b) Decomposition of the change in welfare

Notes: The figure shows changes in welfare following a unilateral increase in the EU carbon price from \$15 to \$105 per ton. Subfigure (a) shows the distribution of the change in economic costs, and subfigure (b) shows the average contribution of its different components. Welfare is defined as the sum of consumer surplus, profits, government revenue after taxes, subsidies, and tariffs, and environmental benefits expressed in 2018 \$US. Welfare changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X. Country-specific values of SCC are computed following Farrokhi and Lashkaripour (2025).

Table 2.5: Impact of EU Carbon Price Increase on EU Welfare and Global Emissions for Alternative Parameter Estimates

	(i) Government Revenue	(ii) Consumer Surplus	(iii) Profits	(iv) Economic Costs = (i)+(ii)+(iii)	(v) Environmental Benefit	(vi) Welfare = (iv) + (v)	(vii) Global Abatement [%]
A. Excluding Outliers in Elasticities							
No-BAM	64.5	-96.9	-22.4	-54.8	36.3	-18.5	1.02
CBAM-EU	66.2	-98.8	-21.5	-54.0	37.4	-16.6	1.05
CBAM-ID	122.8	-144.2	-8.6	-30.1	49.3	19.2	1.39
CBAM-EZ	116.9	-138.8	-9.8	-31.7	46.8	15.1	1.32
LBAM	73.1	-105.3	-18.2	-50.4	38.6	-11.8	1.09
LBAM-X	31.5	-105.3	22.0	-51.8	44.2	-7.6	1.25
B. Capital Stock via Perpetual Inventory Method (PIM)							
No-BAM	37.8	-54.6	-15.0	-31.8	19.3	-12.5	0.75
CBAM-EU	39.3	-56.5	-14.0	-31.2	21.4	-9.7	0.83
CBAM-ID	78.6	-93.8	-2.7	-17.8	34.9	17.1	1.35
CBAM-EZ	73.1	-87.3	-4.6	-18.8	31.5	12.8	1.22
LBAM	45.7	-62.5	-11.6	-28.4	22.3	-6.1	0.86
LBAM-X	24.0	-62.5	9.6	-29.0	26.5	-2.5	1.02
C. Constant returns to scale and demand elasticity for all sectors							
No-BAM	62.7	-72.4	-24.3	-34.0	26.5	-7.5	0.64
CBAM-EU	64.5	-74.5	-23.1	-33.1	27.8	-5.3	0.67
CBAM-ID	100.0	-118.3	-5.3	-23.6	58.2	34.6	1.40
CBAM-EZ	96.8	-111.8	-8.1	-23.1	51.2	28.1	1.23
LBAM	76.8	-87.1	-17.3	-27.6	34.9	7.3	0.84
LBAM-X	56.9	-87.1	1.6	-28.6	45.0	16.4	1.08

Notes: This table reports the change in EU welfare (vi) and its components (i-iii, v) following an EU carbon price increase from $15 to $105, in billions of 2018 US$ for alternative parameter estimates. The percentage reduction in global emissions (vii) is relative to 2018 levels and valued at a SCC of $178 per ton to compute the global environmental benefit (v, in billions of 2018 US$). Panel A excludes a broader set of outliers from the output and trade elasticity estimates, Panel B estimates the capital stock using the perpetual inventory method (PIM), while Panel C assumes constant returns to scale ($\gamma = 0$) and a demand elasticity $\varepsilon = 6$ for all industries.

2.7 Conclusion

With the adoption of CBAM, the EU has overcome a long-standing hesitation to restrict free trade in pursuit of environmental goals. As our analysis has shown, however, CBAM covers too few sectors to prevent import leakage effectively, and does not address substantial export leakage. Expanding CBAM's sector coverage is subject to formidable information requirements and would restrict market access more than needed to prevent leakage, imposing heavy welfare losses on some non-EU countries.

The alternative developed in this paper, LBAM, mitigates carbon leakage with minimal information requirements and trade impacts. LBAM neither discriminates between trade partners nor does it make them worse off as the EU-ETS price increases. These features are aligned with the WTO's core principles of national treatment and non-discrimination (Staiger, 2022). For CBAM, however, the EU invokes environmentally-based exceptions from those principles. As several prominent WTO member states firmly reject this view (BRICS, 2025; WTO, 2023; WTO, 2024), CBAM is at risk of becoming a political non-starter. In that case, a "climate club" of countries with a high carbon price would lack a credible instrument to persuade non-members to adopt carbon pricing on their own (G7, 2022; Nordhaus, 2015).

LBAM is a more consensual alternative as it only sterilizes the trade impacts of increasing EU-ETS prices. If other countries implement carbon prices different from the EU's, LBAM tariffs would become partner-country specific. They would still satisfy non-discrimination, as they would guarantee the previous level of market access. Finally, as the EU decarbonizes its own production over time, LBAM tariffs would converge to zero, thus re-establishing free trade.

Appendix to Chapter 2

B.1 Theory Appendix

B.1.1 LBAM

By virtue of holding bilateral imports constant, the tariff changes in condition (2.21) hold fixed the aggregate import quantity. However, in principle, other tariff changes could also hold aggregate imports constant, while leaving bilateral imports free to adjust. To establish uniqueness, we show that there exist no other non-discriminatory tariffs that hold aggregate imports constant.

Consider a scenario where tariffs on imports are set in order to keep changes in aggregate imports equal to zero, i.e. $\hat{C}_{iI} = 1$. First, we need to define total imports, both in levels and in changes:

$$C_{iIs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} \equiv \sum_{j\neq i} C_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}}, \tag{C.27}$$

$$\hat{C}_{iIs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j\neq i} \delta^I_{ijs} \hat{c}_{ijs}^{\frac{\varepsilon_s-1}{\varepsilon_s}} = \sum_{j\neq i} \delta^I_{ijs} \left[\hat{p}_{Zj}^{-\beta_s \frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs}\right)^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \right]^{\frac{\varepsilon_s-1}{\varepsilon_s}}, \tag{C.28}$$

where $\delta^I_{ijs} \equiv \frac{P_{ijs}C_{ijs}}{P_{iIs}C_{iIs}}$ represents the share of imports of country i from country j. Then given condition (C.28)

$$1 = \sum_{j\neq i}^{J} \delta^I_{ijs} \left[\hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{P}_{is}^{\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}} \right]^{\frac{\varepsilon_s-1}{\varepsilon_s}} \Rightarrow \hat{P}_{is}^{-\frac{(\varepsilon_s-1)^2}{(\gamma_s\varepsilon_s+1)\varepsilon_s}} = \sum_{j\neq i}^{J} \delta^I_{ijs} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}. \tag{C.29}$$

At the same time from condition (2.16) it follows:

$$\hat{P}_{is}^{\frac{(1+\gamma_s)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} = \delta_{iis} \hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \sum_{j\neq i}^{J} \delta_{ijs} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}. \tag{C.30}$$

Combining the last two conditions, we have that keeping aggregate imports constant implies the following condition:

$$\left[\sum_{j\neq i}^{J} \delta^I_{ijs} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right]^{\frac{\varepsilon_s(1+\gamma_s)}{(\varepsilon_s-1)}} = \delta_{iis} \hat{p}_{Zi}^{\frac{\beta_s(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \sum_{j\neq i}^{J} \delta_{ijs} \hat{\tau}_{Iijs}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}. \tag{C.31}$$

There is no unique solution to this problem, and thus, there exist multiple tariff schemes that ensure constant aggregate imports. However, when imposing the additional condition that tariffs must be non-discriminatory between partner countries (Most-favored-nation principle), condition (C.31) can be rewritten as condition (2.21). Consequently, holding aggregate imports constant without discriminating between origin countries is equivalent to choosing a tariff change that holds bilateral imports constant.

B. 1.2 Welfare

To write profits and tax income in terms of observables note that from (2.4) and the definition of δ_{jis} we have $p_{jis}c_{jis} = \delta_{jis}\eta_{js}$.

From (2.9):

$$\hat{\Pi}_{jis} = \left(\frac{\hat{y}_{jis}}{\hat{\phi}_{jis}}\right)^{1+\gamma_s} \hat{p}_{Zi}^{\beta_s(\gamma_s+1)}. \tag{C.32}$$

Using (2.7) and (2.9) we can write $\Pi_{jis} = N_{jis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}[1-\mu_s^{-1}(1+\gamma_s)^{-1}]\eta_{js}\delta_{jis}$. Thus,

$$\hat{\Pi}_{is} = \sum_{j=1}^{J} \hat{\Pi}_{jis} \frac{\Pi_{jis}}{\sum_{j=1}^{J}\Pi_{jis}} = \sum_{j=1}^{J} \hat{\Pi}_{jis}\sigma_{jis}, \tag{C.33}$$

where

$$\sigma_{jis} \equiv \frac{\Pi_{jis}}{\sum_{j=1}^{J}\Pi_{jis}} = \frac{\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}{\sum_{j=1}^{J}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}}. \tag{C.34}$$

Hence,

$$\hat{\Pi}_{is} = \hat{p}_{Zi}^{\beta_s(\gamma_s+1)} \sum_{j=1}^{J} \sigma_{jis}\hat{y}_{jis}^{\gamma_s+1} \qquad \Pi_{is} = \left[1 - \frac{1}{\mu_s(1+\gamma_s)}\right] \sum_{j=1}^{J} \tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}.$$

To handle zero initial tax revenues, we write the expression for welfare changes as:

$$\int_s (\hat{T}_{is}-1)T_{is}ds = \int_s (\hat{T}_{Eis}-1)T_{Eis}ds + \int_s (T'_{Iis}-T_{Iis})ds + \int_s (T'_{Xis}-T_{Xis})ds, \tag{C.35}$$

where

$$T_{Eis} \equiv \tau_{Ei}\sum_{j=1}^{J} N_{jis}e_{jis},$$

$$T_{Iis} \equiv \sum_{j\neq i}^{J} (\tau_{Iijs}-1)N_{ijs}\tau_{Iijs}^{-1}p_{ijs}c_{ijs},$$

$$T_{Xis} \equiv \sum_{j\neq i}^{J} (\tau_{Xjis}-1)N_{jis}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}p_{ji}c_{jis}.$$

By (2.4), (2.6), (2.7), (C.34), and the definition of δ_{jis} we have:

$$
\begin{aligned}
\hat{T}_{Eis} &= \hat{\tau}_{Ei}\hat{p}_{Zi}^{\beta_s(1+\gamma_s)-1}\sum_{j=1}^{J}\sigma_{jis}\left(\frac{\hat{y}_{jis}}{\hat{\phi}_{jis}}\right)^{(1+\gamma_s)}, \\
T_{Eis} &= \beta_s\mu_s^{-1}d_i\tau_{Eis}p_{Zi}^{-1}\sum_{j=1}^{J}\tau_{Ijis}^{-1}\tau_{Xjis}^{-1}\eta_{js}\delta_{jis}, \\
T'_{Iis} &= \eta_{is}\sum_{j\neq i}^{J}(\tau'_{Iijs}-1)(\tau'_{Iijs})^{-1}\delta'_{ijs}, \\
T_{Iis} &= \eta_{is}\sum_{j\neq i}^{J}(\tau_{Iijs}-1)\tau_{Iijs}^{-1}\delta_{ijs}, \\
T'_{Xis} &= \sum_{j\neq i}^{J}\eta_{js}(\tau'_{Xjis}-1)(\tau'_{Ijis})^{-1}(\tau'_{Xjis})^{-1}\delta'_{jis}, \\
T_{Xis} &= \sum_{j\neq i}^{J}\eta_{js}(\tau_{Xjis}-1)\tau_{Iji}^{-1}\tau_{Xji}^{-1}\delta_{jis},
\end{aligned}
$$

where $\delta'_{ijs} = \delta_{ijs}\hat{\delta}_{ijs} = \delta_{ijs}\hat{p}_{ijs}\hat{y}_{ijs}$.

B. 1.3 LBAM and LBAM-X in the Presence of Productivity Shocks

In this section, we derive LBAM and LBAM-X policies for the case when $\hat{\phi}_{ijs} \neq 1$. Specifically, we show that LBAM-X export subsidies are always independent of productivity shocks. Thus, LBAM-X export subsidies exactly sterilize the effect of carbon price shocks in the origin country on export prices, while productivity shocks in the origin country are completely passed through to consumers in the destination market. For LBAM tariffs, we show that they are independent of productivity shocks as long as these are sector-specific, i.e., $\hat{\phi}_{ijs} = \hat{\phi}_{is} \quad \forall j$. For the most general case in which productivity shocks vary at the importer-exporter-sector level ($\hat{\phi}_{ijs}$), non-discriminatory LBAM tariffs still remain independent of productivity shocks up to a first-order approximation.

As a first step, it is useful to substitute (2.16) into (2.13) to obtain $\hat{y}_{ijs}$ as a function of productivity shocks and policy instruments:

$$\hat{y}_{ijs} = \left(\hat{\phi}_{ijs}\hat{p}_{Zj}^{-\beta_s}\right)^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\hat{\tau}_{Iijs}\hat{\tau}_{Xijs}\right)^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \times \left(\sum_{k=1}^{K} \delta_{iks}\left(\hat{\phi}_{iks}\hat{p}_{Zk}^{-\beta_s}\right)^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \left(\hat{\tau}_{Iiks}\hat{\tau}_{Xiks}\right)^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}\right)^{\frac{-1}{\gamma_s+1}}. \tag{C.36}$$

Next, we compute the change in country i's imports and exports induced exclusively by productivity shocks by imposing $\hat{p}_{Zi} = 1$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Xjis} = 1$ in (C.36):

$$\hat{y}_{ijs} = \hat{\phi}_{ijs}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\sum_{k=1}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{\frac{-1}{1+\gamma_s}}, \tag{C.37}$$

$$\hat{y}_{jis} = \hat{\phi}_{jis}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\sum_{k=1}^{K} \delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{\frac{-1}{1+\gamma_s}}. \tag{C.38}$$

LBAM

If we consider LBAM tariffs in country i only (i.e., $\hat{p}_{Zi} > 1$ and $\hat{\tau}_{Iijs} \neq 1$ for country i, $\hat{p}_{Zj} = 1$ for $j \neq i$, $\hat{\tau}_{Ikjs} = 1$ for $k \neq i$, and $\hat{\tau}_{Xijs} = 1$ for all for i, j), condition (C.36) simplifies to:

$$\hat{y}_{ijs} = \hat{\phi}_{ijs}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Iijs}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}\left(\hat{\phi}_{iis}\hat{p}_{Zi}^{-\beta_s}\right)^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Iiks}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}}\right)^{\frac{-1}{1+\gamma_s}}. \tag{C.39}$$

In the main text, we computed LBAM tariffs for the case $\hat{\phi}_{ijs} = 1 \forall i, j, s$ by imposing $\hat{y}_{ijs} = 1$, and we showed that they are non-discriminatory and implicitly defined by:

$$\hat{\tau}_{Iis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}\hat{p}_{Zi}^{\beta_s \frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} + \hat{\tau}_{Iis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \sum_{k\neq i}^{K} \delta_{iks}\right)^{\frac{-1}{1+\gamma_s}} = 1. \tag{C.40}$$

When $\hat{\phi}_{ijs} \neq 1$, we need to verify that LBAM tariffs exclusively sterilize the effect of a change in the domestic carbon price on imports, without interfering with the adjustment of imports to productivity shocks, i.e., imports should change according to (C.37). By combining (C.39) with (C.37) we obtain the necessary and sufficient conditions that LBAM tariffs need to satisfy to exclusively sterilize the impact of changes in the domestic carbon price:

$$\delta_{iis}\hat{\phi}_{iis}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \tag{C.41}$$

$$= \hat{\tau}_{Iijs}^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}(\hat{\phi}_{iis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \hat{\tau}_{Iiks}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right). \tag{C.42}$$

If productivity shocks are sector-specific but not origin-country-specific, i.e. $\hat{\phi}_{ijs} = \hat{\phi}_{is} \forall j$, then (C.41) simplifies to:

$$\hat{\tau}_{Iis}^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \left(\delta_{iis}\hat{p}_{Zi}^{-\beta_s \frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}^{K} \delta_{iks}\hat{\tau}_{Iiks}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \right) = 1. \tag{C.43}$$

Note that (C.43) is identical for all origin countries j, implying that the tariff is non-discriminatory. Once we impose $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis} \quad \forall j$ then (C.43) coincides with (C.40). Hence, non-discriminatory LBAM tariffs exactly sterilize the change in the carbon price while passing through sector-specific changes in productivity. Specifically, imposing $\hat{\phi}_{ijs} = \hat{\phi}_{is}$ and $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}$ in (C.39) and using (C.40) we obtain $\hat{y}_{ijs} = \hat{\phi}_{is}$ which coincides with (C.37) when productivity shocks are sector-specific.

If productivity shocks are, instead, sector-country-specific, LBAM tariffs that satisfy (C.41) cannot be non-discriminatory. Indeed, if we assume $\hat{\tau}_{Iijs} = \hat{\tau}_{Iis}\forall j$, (C.41) simplifies to:

$$\delta_{ii}\hat{\phi}_{iis}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} \left(\hat{p}_{Zi}^{\beta_s \frac{(\gamma_s+1)(1-\varepsilon_s)}{\gamma_s\varepsilon_s+1}} - \hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} \right)$$
$$= \hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} (1-\hat{\tau}_{Iis}) \sum_{k\neq i}^{K} \delta_{iks}\hat{\phi}_{iks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}. \tag{C.44}$$

Notice that δ_{iks} and $\hat{\phi}_{iks}^{-1}$ are exogenously given. Hence, for (C.44) to be satisfied for any possible realization of $\hat{\phi}_{iks}$, we would need both $\hat{\tau}_{Iis} = \hat{p}_{Zi}^{\frac{\varepsilon-1}{\varepsilon}}$ and τ_{Iis}=1.This is possible only when $\hat{p}_{Zi} = 1$. Thus, in this case, LBAM tariffs that exclusively sterilize carbon price shocks cannot be non-discriminatory.

However, even if non-discriminatory LBAM tariffs as implied by condition (C.40) do not exclusively sterilize the effect of carbon price shocks when productivity shocks are country-sector-specific, they do it up to a first-order approximation.

To show this, we take a log-linear approximation of (C.41) and use it to derive the LBAM tariffs that solve the approximated equation. Then, we check whether these tariffs coincide, up to the first order, with our original solution in (C.40). In what follows, we use the fact that $\hat{x} = e^{\log \hat{x}}$, and we indicate with $\log \hat{x}^*$ the value of the variable at the approximation point. As a first step, we take the first-order approximation of condition (C.41) around an equilibrium where shocks are sector-specific, i.e. $\hat{\phi}^*_{ijs} = \hat{\phi}^*_{is} \quad \forall j$. Then, by condition (C.43), LBAM tariffs are non-discriminatory, i.e. $\hat{\tau}^*_{ijs} = \hat{\tau}^*_{is}$. Thus, by linearizing condition (C.41) w.r.t. $\log \hat{x}$ we obtain:

$$
\begin{aligned}
&\delta_{iis}\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}\left(\log\hat{\phi}_{iis}-\log\hat{\phi}^*_{is}\right)\\
&\quad+\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}\sum_{k\neq i}^{K}\delta_{iks}\left(\log\hat{\phi}_{iks}-\log\hat{\phi}^*_{is}\right)\\
&=\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}(\hat{\tau}^*_{Iis})^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}}\delta_{iis}(\hat{p}^*_{Zi})^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}(\log\hat{\tau}_{Iijs}-\log\hat{\tau}^*_{Iis})\\
&\quad+\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}(\hat{\tau}^*_{Iis})^{\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}}\delta_{iis}(\hat{p}^*_{Zi})^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\\
&\quad\times\left[\left(\log\hat{\phi}_{iis}-\log\hat{\phi}^*_{is}\right)-\beta_s(\log\hat{p}_{Zi}-\log\hat{p}^*_{Zi})\right]\\
&\quad+\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}\hat{\tau}^*_{Iis}(1-\delta_{iis})(\log\hat{\tau}_{Iijs}-\log\hat{\tau}^*_{Iis})\\
&\quad+\hat{\tau}^*_{Iis}\sum_{k\neq i}^{K}\delta_{iks}\left[\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}\left(\log\hat{\phi}_{iks}-\log\hat{\phi}^*_{is}\right)\right.\\
&\qquad\left.-\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}(\log\hat{\tau}_{Iiks}-\log\hat{\tau}^*_{Iis})\right].
\end{aligned}
\tag{C.45}
$$

Next, we impose that at the point of approximation there are no policies in place, i.e., $\hat{\tau}^*_{Iis} = \hat{p}^*_{zi} = 1$ to obtain:

$$
\varepsilon_s(\gamma_s+1)\log\hat{\tau}_{Iijs} = \beta_s(\gamma_s+1)(\varepsilon_s-1)\delta_{iis}\log\hat{p}_{Zi} + (\varepsilon_s-1)\sum_{k\neq i}^{K}\delta_{iks}\log\hat{\tau}_{Iiks}. \tag{C.46}
$$

Condition (C.46) implies that, up to a first-order approximation, LBAM tariffs for the general case where $\hat{\phi}_{ijs} \neq 1$ do not need to be discriminatory across origin countries. We can thus assume that $\log\hat{\tau}_{Iijs} = \log\hat{\tau}_{Iis}\forall j$ to rewrite (C.46) as follows:

$$
\varepsilon_s(\gamma_s+1)\log\hat{\tau}_{Iis} = \beta_s(\gamma_s+1)(\varepsilon_s-1)\delta_{iis}\log\hat{p}_{Zi} + (\varepsilon_s-1)(1-\delta_{iis})\log\hat{\tau}_{Iis}. \tag{C.47}
$$

As a final step, we need to take a first-order approximation of (C.40) around the same equilibrium and show that it coincides with (C.47). First, note that we can rewrite this condition as follows:

$$
\hat{\tau}_{Iis}^{\frac{-\varepsilon_s(1+\gamma_s)}{\gamma_s\varepsilon_s+1}} = \delta_{iis}\hat{p}_{Zi}^{-\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \hat{\tau}_{Iis}^{-\frac{\varepsilon_s-1}{\gamma_s\varepsilon_s+1}}(1-\delta_{iis}). \tag{C.48}
$$

Taking a log-linear approximation of (C.48) we obtain exactly (C.47). This proves our conjecture.

LBAM-X

If we consider LBAM-X export subsidies in country i only (i.e., $\hat{p}_{Zi} > 1$ and $\hat{\tau}_{Xjis} \neq 1$ for country i, $\hat{p}_{Zj} = 1$ for $j \neq i$, $\hat{\tau}_{Iijs} = 1$ for all for i, j, and $\hat{\tau}_{Xjks} = 1$ for $k \neq i$) then condition (C.36) simplifies to:

$$\begin{aligned}\hat{y}_{jis} = {} & (\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}}\hat{\tau}_{Xjis}^{\frac{-\varepsilon_s}{\gamma_s\varepsilon_s+1}} \\ & \times \left(\delta_{jis}(\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\hat{\tau}_{Xjis}^{\frac{1-\varepsilon_s}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}\delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{-\frac{1}{1+\gamma_s}}.\end{aligned} \tag{C.49}$$

In the main text we showed that when $\hat{\phi}_{jis} = 1$, the non-discriminatory export subsidy for which $\hat{y}_{jis} = 1 \forall j \neq i$ is given by $\hat{\tau}_{Xjis} = \hat{p}_{Zi}^{-\beta_s(\gamma_s+1)}$. If we substitute this LBAM-X subsidy into (C.49) we get:

$$\begin{aligned}\hat{y}_{jis} &= (\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}}\hat{p}_{Zi}^{\beta_s\frac{\varepsilon_s(\gamma_s+1)}{\gamma_s\varepsilon_s+1}} \\ &\quad \times \left(\delta_{jis}(\hat{\phi}_{jis}\hat{p}_{Zi}^{-\beta_s})^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\hat{p}_{Zi}^{\beta_s\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}\delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{-\frac{1}{1+\gamma_s}} \\ &= \hat{\phi}_{jis}^{\frac{(\gamma_s+1)\varepsilon_s}{\gamma_s\varepsilon_s+1}}\left(\delta_{jis}\hat{\phi}_{jis}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}} + \sum_{k\neq i}\delta_{jks}\hat{\phi}_{jks}^{\frac{(\gamma_s+1)(\varepsilon_s-1)}{\gamma_s\varepsilon_s+1}}\right)^{-\frac{1}{1+\gamma_s}},\end{aligned} \tag{C.50}$$

which coincides with (C.38). This result implies that the LBAM-X export subsidy is independent of productivity shocks: while it sterilizes the effect of a change in the domestic carbon price on exports, it does not interfere with fluctuations in exports due to domestic or foreign productivity shocks.

B. 2 Data Appendix

B. 2.1 Imputation of Fuel Consumption

Table B.1 reports the outcome and goodness of fit for the imputation of fuel consumption by energy type. With our preferred regression specification, we achieve an R^2 above 0.7 for all four fuel types. Table B.3 presents summary statistics of imputed and non-imputed fuel shares. Electricity, followed by natural gas, are the most used fuel types in our sample. The share of imputed observations ranges between 8 and 26%.

Table B.1: Imputation of Fuel Consumption

	Log Fuel consumption			
	Electricity (1)	Oil (2)	Natural Gas (3)	Coal (4)
Log GDP per capita	0.436	1.022*	1.374*	1.302
	(0.312)	(0.394)	(0.661)	(0.738)
Log Population	0.593	0.708*	1.007	2.229***
	(0.302)	(0.306)	(0.690)	(0.625)
Log Capital stock	0.382	0.136	-0.132	-0.624
	(0.275)	(0.278)	(0.574)	(0.505)
Dummy oil		0.234		
		(0.271)		
Dummy natural gas			1.473*	
			(0.580)	
Dummy coal				1.243
				(0.664)
Region FE	Yes	Yes	Yes	Yes
Sub-region FE	Yes	Yes	Yes	Yes
N	67	67	53	57
Within R2	0.789	0.771	0.707	0.735

Notes: This table presents estimates from OLS regressions used to impute missing fuel consumption values. The dependent variable in each column is the log of fuel consumption: electricity (Column 1), oil (Column 2), natural gas (Column 3), and coal (Column 4). Independent variables include log GDP per capita, log population, log capital stock, and a dummy variable indicating the production of each respective fuel type. All regressions include region and sub-region fixed effects. Standard errors are reported in parentheses. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

B. 2.2 Imputation of Fuel Prices

Table B.2 reports the outcome and goodness of fit for the imputation of fuel prices by energy type. We run our preferred regression specification on a dataset that includes both official IEA and our hand-collected prices to increase the number of observations. We achieve an R^2 between 0.09 for electricity and 0.48 for coal. The low goodness of fit is driven by considerable heterogeneity across countries in fuel prices (see Table B.4). While we have industry electricity prices for nearly all countries, with a share of imputed observations of 6%, we have to impute prices for roughly 50% or more observations for the other fuel types. For the ten largest countries in terms of fuel consumption, we hand-collected fuel prices and do not rely on imputed prices.

Table B.2: Imputation of Fuel Prices

	Log Fuel price			
	Electricity (1)	Oil (2)	Natural Gas (3)	Coal (4)
Log GDP per capita	-0.660	-0.080	-0.395	-2.006***
	(0.380)	(0.126)	(0.505)	(0.413)
Log Population	-0.541	-0.053	-0.108	-1.512**
	(0.394)	(0.120)	(0.353)	(0.333)
Log Capital stock	0.495	0.006	0.075	1.107**
	(0.381)	(0.117)	(0.343)	(0.307)
Dummy oil		-0.084		
		(0.086)		
Dummy natural gas			-0.045	
			(0.029)	
Dummy coal				0.500
				(0.224)
Region FE	Yes	Yes	Yes	Yes
Sub-region FE	Yes	Yes	Yes	Yes
N	105	59	38	21
Within R2	0.085	0.139	0.215	0.478

Notes: This table presents estimates from OLS regressions used to impute missing fuel prices. The dependent variable in each column is the log of fuel consumption: electricity (Column 1), oil (Column 2), natural gas (Column 3), and coal (Column 4). Independent variables include log GDP per capita, log population, log capital stock, and a dummy variable indicating the production of each respective fuel type. All regressions include region and sub-region fixed effects. Standard errors are reported in parentheses. Significance levels are indicated as * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table B.3: Summary Statistics Fuel Shares

	N	Mean	Median	Min	Max	SD	% imputed
Fuel share coal	74	0.175	0.114	0.000	0.605	0.164	0.216
Fuel share electricity	74	0.327	0.327	0.048	0.970	0.147	0.081
Fuel share natural gas	74	0.275	0.234	0.005	0.804	0.213	0.257
Fuel share oil	74	0.223	0.165	0.018	0.766	0.178	0.081

Notes: Column 1 reports the number of observations for each fuel share variable. Columns 2 and 3 report the mean and standard deviation of each fuel share variable across all observations. Columns 4 to 6 present the median, minimum, and maximum values for each fuel share. Column 7 shows the percentage of imputed data for each fuel share variable.

Table B.4: Summary Statistics Fuel Prices

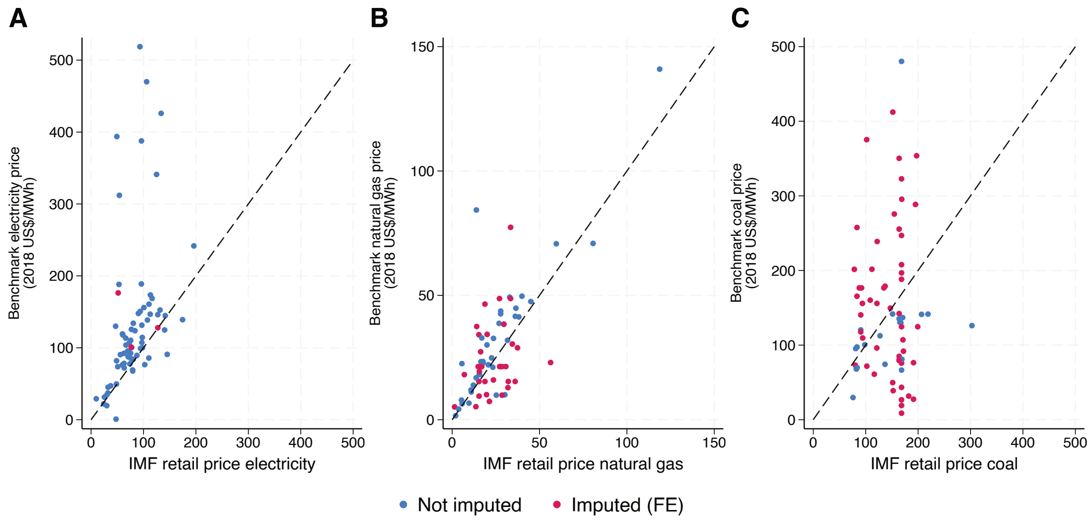
	N	Mean	Median	Min	Max	SD	% imputed
Price coal	74	146.564	127.837	8.736	480.300	97.224	0.716
Price electricity	74	133.405	107.044	0.777	518.742	101.327	0.055
Price oil	74	569.616	549.311	134.010	1026.786	155.381	0.486
Price natural gas	74	21.646	11.556	0.210	140.970	26.774	0.473

Notes: Column 1 reports the number of observations for each fuel price variable. Columns 2 and 3 report the mean and standard deviation of the fuel prices across all observations. Columns 4 to 6 present the median, minimum, and maximum values for each fuel price variable. Column 7 shows the percentage of imputed data for each fuel price variable.

B. 2.3 Comparison with IMF Energy Prices

Getting the energy prices right is crucial for the validity of our results. To assess our approach of collecting data from different sources and imputing missing data using OLS regressions, we compare our data with Black et al. (2023), a readily available dataset. Figure B.1 plots our benchmark price data against IMF data for electricity, natural gas and coal. Overall, our benchmark data show a wider dispersion than the IMF data and suggest higher energy prices on average. This is most pronounced for electricity and coal. Natural gas prices are the most similar. In general, given a sufficient number of data points, our imputation method predicts prices that are no more different from the IMF data than from the prices we collect. In the case of coal, the lack of data points leads to a wider dispersion of coal prices than observed in the IMF data. The differences between our benchmark and the IMF prices can mainly be explained by two factors. First, the IMF primarily uses IMF and World Bank country desk data, while we rely on IEA data. Second, when industry prices are missing, even after using reliable third-party sources such as the IEA and Eurostat, the IMF uses prices from the electricity sector or import prices to impute these observations. Overall, we prefer to use our, on average, higher benchmark energy prices as they give us more conservative results for welfare, emissions, and trade effects. As a result, the negative economic impact on foreign countries is smaller than when using the IMF data.

Figure B.1: Comparison of IMF prices and collected prices for different fuel types



Notes: This figure depicts scatter plots of (**A**) collected electricity prices as the dependent variable and IMF electricity retail prices as independent variable, (**B**) collected natural gas as dependent variable and IMF natural gas prices as independent variable, and (**C**) collected coal prices as dependent variable and IMF coal prices as independent variable. IMF prices are deflated using the FRED Global Price of Energy Index.

B. 3 Additional Tables

Table B.5: Policy-Induced Changes in EU Imports by 2-digit Sector

Description	ISIC	No-BAM	CBAM-EU	CBAM-ID	CBAM-EZ	LBAM	LBAM-X
Food	10	22.5	22.5	-9.3	-10.8	0.0	0.0
Beverages	11	52.6	52.6	-10.6	-15.7	0.0	0.0
Tobacco	12	6.7	6.7	-15.0	-14.5	0.0	0.0
Textiles	13	0.9	0.9	-7.0	-5.2	0.0	0.0
Apparel	14	2.3	2.3	-9.6	-6.6	0.0	0.0
Leather	15	2.6	2.6	-10.2	-6.7	0.0	0.0
Wood	16	0.5	0.5	-4.9	-3.9	0.0	0.0
Paper	17	0.6	0.6	-4.2	-4.3	0.0	0.0
Printing	18	2.3	2.3	-4.8	-4.2	0.0	0.0
Petroleum	19	0.0	0.0	-4.6	-4.1	0.0	0.0
Chemicals	20	2.4	2.2	-7.3	-6.6	-0.0	-0.0
Pharma	21	6.4	6.4	-9.3	-10.4	0.0	0.0
Plastics	22	0.6	0.6	-8.3	-6.4	0.0	0.0
Minerals	23	17.5	17.4	-20.7	-16.9	0.0	0.0
Metals	24	4.7	-6.2	-6.6	-6.4	0.0	0.0
Metalwork	25	3.0	3.0	-8.2	-6.1	0.0	0.0
Electronics	26	5.8	5.8	-13.0	-9.5	0.0	0.0
Electrical	27	2.3	2.3	-6.4	-4.8	0.0	0.0
Machinery	28	3.4	3.4	-3.1	-2.7	0.0	0.0
Vehicles	29	11.5	11.5	-7.9	-7.1	0.0	0.0
Transport	30	1.1	1.1	-3.6	-2.7	0.0	0.0
Furniture	31	0.0	0.0	-1.3	-1.0	0.0	0.0
Misc	32	0.2	0.2	-0.8	-1.9	0.0	0.0
Repair	33	0.1	0.1	-7.6	-6.2	0.0	0.0

Notes: The table reports the change in EU imports for 2-digit ISIC sectors following an EU carbon price increase from $15 to $105, in billions of 2018 US$. The percentage change in EU imports is relative to 2018 levels.

Table B.6: Policy-Induced Changes in EU Exports by 2-digit Sector

Description	ISIC Code	No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, and LBAM	LBAM-X
Food	10	-24.0	0.0
Beverages	11	-31.6	0.0
Tobacco	12	-11.2	0.0
Textiles	13	-3.9	0.0
Apparel	14	-5.1	0.0
Leather	15	-7.5	0.0
Wood	16	-2.4	0.0
Paper	17	-3.1	0.0
Printing	18	-3.4	0.0
Petroleum	19	-2.8	0.0
Chemicals	20	-6.4	0.0
Pharma	21	-11.1	0.0
Plastics	22	-4.0	0.0
Minerals	23	-11.3	0.0
Metals	24	-6.8	0.0
Metalwork	25	-3.8	0.0
Electronics	26	-29.2	0.0
Electrical	27	-4.0	0.0
Machinery	28	-3.4	0.0
Vehicles	29	-11.5	0.0
Transport	30	-2.2	0.0
Furniture	31	-0.5	0.0
Misc	32	-7.6	0.0
Repair	33	-5.0	0.0

Notes: The table reports the change in EU exports for 2-digit ISIC sectors following an EU carbon price increase from $15 to $105, in billions of 2018 US$. The percentage change in EU exports is relative to 2018 levels.

Table B.7: Policy-Induced Changes in Emissions by 2-digit Sector

Description	ISIC	No-BAM	CBAM-EU	CBAM-ID	CBAM-EZ	LBAM	LBAM-X
Food	10	-1.4	-1.4	-1.7	-1.6	-1.5	-1.8
Beverages	11	-1.2	-1.2	-1.4	-1.4	-1.3	-2.3
Tobacco	12	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Textiles	13	-0.3	-0.3	-0.9	-0.7	-0.4	-0.5
Apparel	14	-0.6	-0.6	-1.3	-1.1	-0.7	-0.7
Leather	15	-0.7	-0.7	-1.4	-1.2	-0.8	-1.1
Wood	16	-1.0	-1.0	-1.4	-1.3	-1.0	-1.0
Paper	17	-2.1	-2.1	-2.3	-2.2	-2.1	-2.0
Printing	18	-2.0	-2.0	-2.1	-2.1	-2.0	-2.0
Petroleum	19	-0.3	-0.3	-0.4	-0.3	-0.3	-0.3
Chemicals	20	-0.8	-0.8	-1.1	-1.1	-0.8	-0.9
Pharma	21	-1.8	-1.8	-2.4	-2.4	-1.9	-2.2
Plastics	22	-1.8	-1.8	-2.2	-2.1	-1.9	-1.8
Minerals	23	-0.4	-0.4	-0.6	-0.6	-0.5	-0.5
Metals	24	-0.6	-1.3	-1.3	-1.1	-0.7	-0.8
Metalwork	25	-1.3	-1.3	-1.6	-1.5	-1.4	-1.4
Electronics	26	0.9	0.9	-0.7	-0.3	0.6	-0.4
Electrical	27	-0.6	-0.6	-1.8	-1.5	-0.9	-1.0
Machinery	28	-1.3	-1.3	-2.1	-2.0	-1.7	-2.3
Vehicles	29	-2.1	-2.1	-2.3	-2.3	-2.2	-2.6
Transport	30	-0.9	-0.9	-1.3	-1.2	-1.0	-1.0
Furniture	31	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9
Misc	32	0.9	0.9	-0.9	-0.4	0.8	-0.8
Repair	33	-0.9	-0.9	-2.4	-2.1	-0.9	-0.9

Notes: The table reports the change in global emissions for 2-digit ISIC sectors following an EU carbon price increase from $15 to $105. The percentage change in global sectoral emissions is relative to 2018 levels.

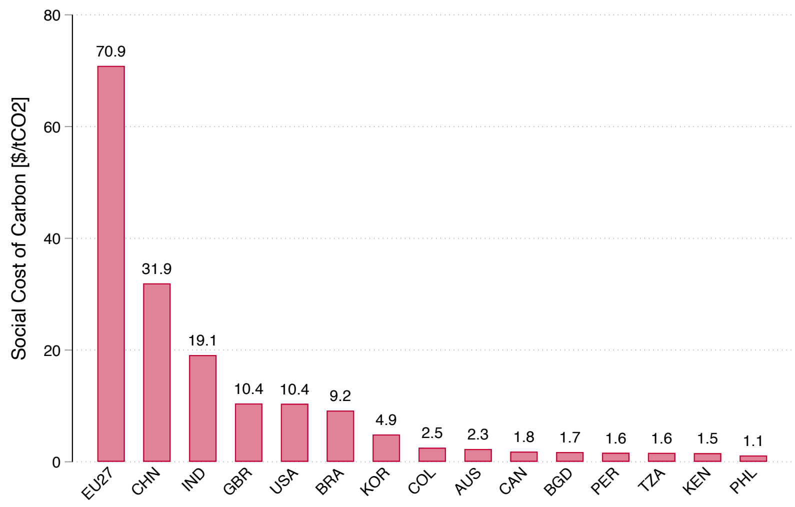
Table B.8: Summary Statistics of Production Function Parameters and Demand Elasticities or Alternative Parameter Estimates

	N	Mean	Median	SD	Min	Max
A. Excluding Outliers in Elasticities						
α_s	131	0.614	0.664	0.282	0.073	0.993
β_s	131	0.097	0.075	0.088	0.003	0.393
γ_s	131	1.117	0.290	1.971	0.000	11.545
ϵ_s	131	3.296	2.368	2.769	1.317	18.078
B. Capital Stock via PIM						
α_s	131	0.656	0.735	0.290	0.078	0.996
β_s	131	0.055	0.024	0.072	0.001	0.315
γ_s	131	1.117	0.290	1.971	0.000	11.545
ϵ_s	131	3.296	2.368	2.769	1.317	18.078
C. Setting $\gamma = 0$ and $\varepsilon = 6$ for all Industries						
α_s	131	0.930	0.965	0.073	0.685	0.998
β_s	131	0.070	0.035	0.073	0.002	0.315
γ_s	131	0.000	0.000	0.000	0.000	0.000
ϵ_s	131	6.000	6.000	0.000	6.000	6.000

Notes: Column 1 reports the number of observations for each parameter. Columns 2 and 3 show the mean and standard deviation for each parameter across all observations. Columns 4 to 6 present the median, minimum, and maximum values for each parameter. Panel A excludes a broader set of outliers from the output and trade elasticity estimates, Panel B estimates the capital stock using the perpetual inventory method (PIM), while Panel C assumes constant returns to scale ($\gamma = 0$) and a demand elasticity $\varepsilon = 6$ for all industries.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung (1998–2018), AFiD-Panel Industriebetriebe (1998–2018), AFiD-Panel Industrieunternehmen (1998–2018), project-specific preparations, own calculations.

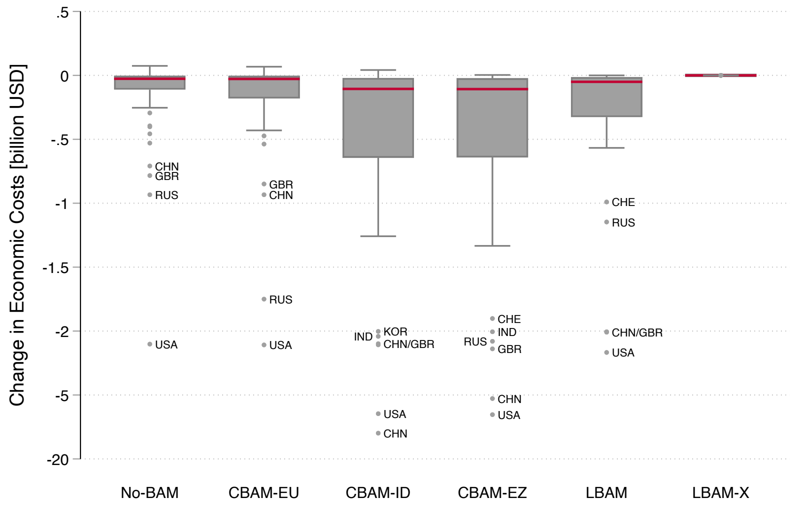
B. 4 Additional Figures

Figure B.2: Country-specific Social Cost of Carbon

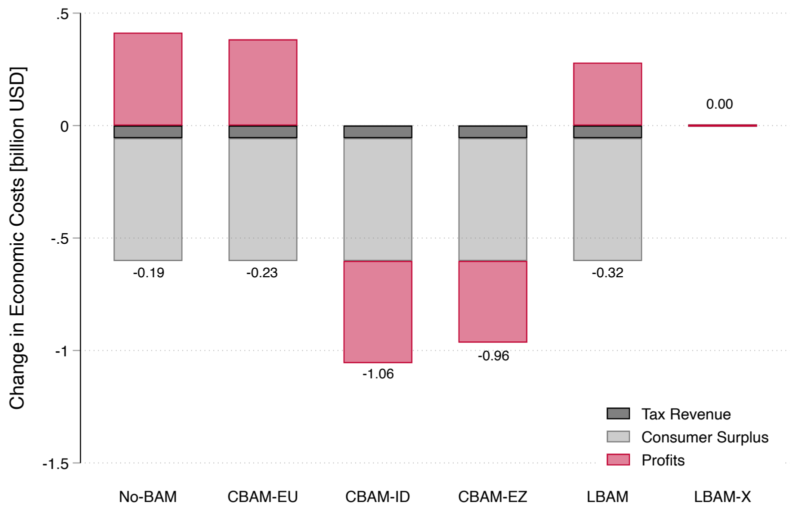


Notes: The figure displays the 15 highest country-specific social cost of carbon (SCC) estimates when allocating the global SCC estimate of $178 by Rennert et al. (2022) across countries using the method proposed by Farrokhi and Lashkaripour (2025).

Figure B.3: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries for Alternative Trade and Output Elasticity Estimates



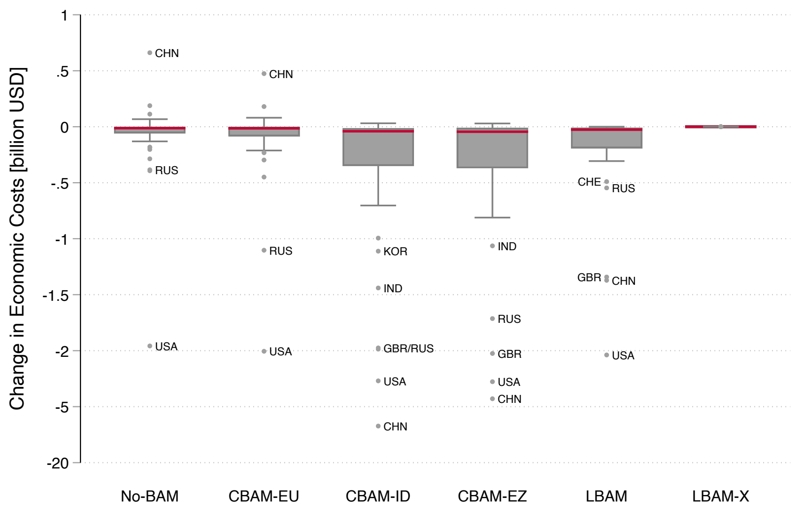
(a) Distribution of the changes in economic costs



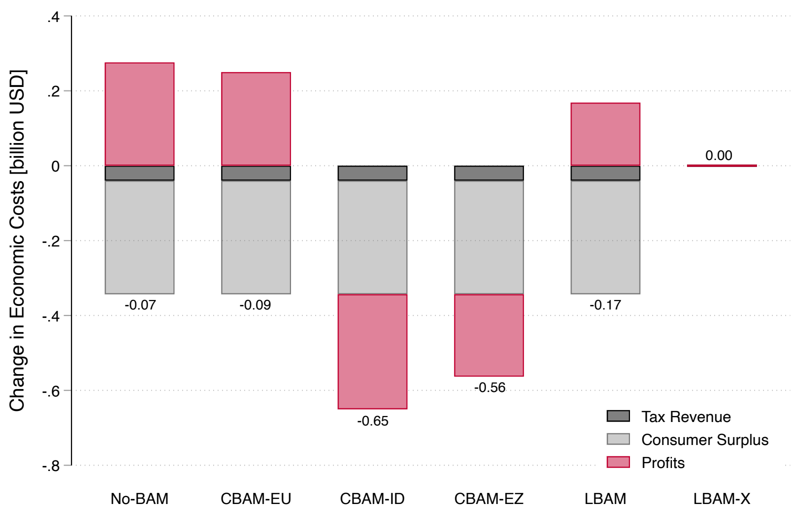
(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from $15 to $105 per ton, under an alternative specification that excludes a broader set of outliers from the output and trade elasticity estimates. Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

Figure B.4: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries for Alternative Capital Stock



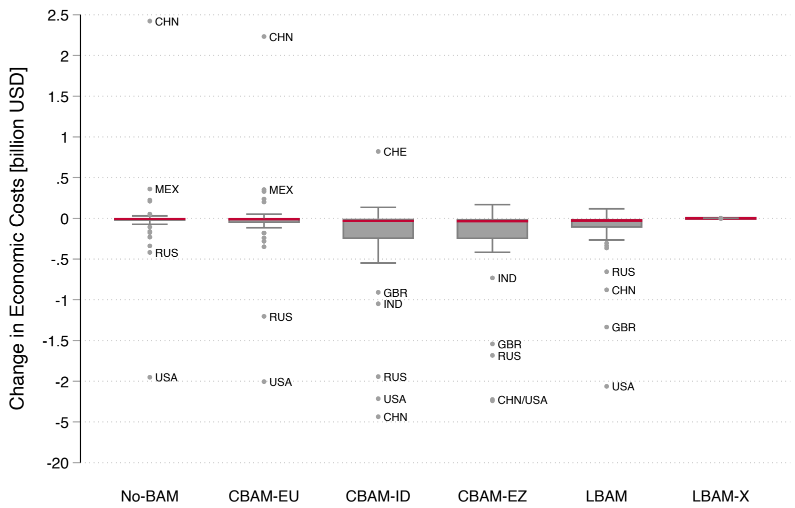
(a) Distribution of the changes in economic costs



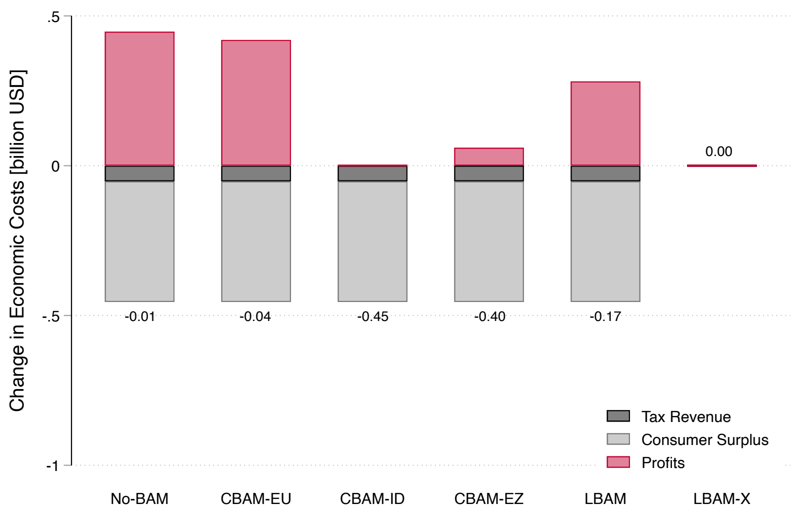
(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from \$15 to \$105 per ton, under an alternative specification that excludes a broader set of outliers from the output and trade elasticity estimates and estimates the capital stock using the perpetual inventory method (PIM). Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US\$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

Figure B.5: Impact of EU Carbon Price Increase on Economic Costs for Non-EU Countries for CRS ($\gamma = 0$) and Standard Choice of Trade Elasticity ($\varepsilon = 6$)



(a) Distribution of the changes in economic costs



(b) Decomposition of the change in economic costs

Notes: The figure shows changes in economic costs following a unilateral increase in the EU carbon price from $15 to $105 per ton, under an alternative specification that excludes a broader set of outliers from the output elasticity estimates and assumes constant returns to scale ($\gamma = 0$) and a demand elasticity $\varepsilon = 6$ for all industries. Subfigure (a) shows the distribution of the change in economic costs, subfigure (b) shows the average contribution of its different components. Economic costs are defined as the sum of consumer surplus, profits, and government revenue after taxes, subsidies, and tariffs, expressed in 2018 US$. Economic costs changes are computed for six different scenarios: No-BAM, CBAM-EU, CBAM-ID, CBAM-EZ, LBAM, and LBAM-X.

3 The Price of Power: Energy Tax Exemptions and Misallocation in Germany

3.1 Introduction

Countries around the world face a fundamental policy dilemma: how to decarbonize production while preserving the international competitiveness of their firms. The introduction of a unilateral domestic carbon price to reduce emissions and limit global warming raises the cost of fossil-fuel–based inputs directly and indirectly. These higher input costs are partially passed through to final goods prices (Ganapati et al., 2020) and cause carbon leakage, defined as the relocation of production and emissions to countries with weaker regulation. This poses particular challenges for economies with a large share of emissions-intensive, trade-exposed industries as they lose competitiveness both in the domestic and foreign markets, resulting in potentially large welfare losses. At the same time, an increase in foreign emissions might offset domestic emission reductions (Fowlie et al., 2016). [1]

To mitigate the leakage effects of climate policies and high energy prices in general, German policymakers have implemented targeted industrial policy. The government granted partial or full exemptions from energy-related taxes to a limited set of large firms (Gerster and Lamp, 2024). These exemptions complement EU-level instruments aimed at limiting leakage, such as the free allocation of EU ETS permits and the Carbon Border Adjustment Mechanism (CBAM), which prices emissions embodied in imports at the EU carbon price.[2] All three policies aim to reduce leakage, but only free allocations and energy-related tax exemptions lower production costs to limit export and import leakage. In contrast, CBAM targets only import leakage by raising the price of foreign goods.

This paper studies the role of industrial policy for both firm-level and aggregate economic and environmental outcomes, with a focus on exports. Using detailed firm-level data on energy-related tax exemptions for Germany, I demonstrate that these exemptions are concentrated among a few industries and firms, contributing substantially to energy price heterogeneity in Germany. However, there seems to be no correlation between tax exemptions and the export performance of an industry. Based on these findings, I develop a quantitative model with heterogeneous firms to study the general equilibrium effects of tax exemptions on emissions, exports, and welfare.

Energy subsidies are among the EU's largest industrial policy instruments. In 2023, spending reached €354 billion, with over one-third allocated to fossil fuels despite the EU's climate

[1] At the same time, effective climate policies can incentivize firms to invest in energy-efficient technologies (Colmer et al., 2025) and generate tax revenue for governments to fund infrastructure critical to the energy transition, both of which can help offset competitiveness losses over the long run.

[2] The scope of CBAM is limited to only a few, narrowly defined industries deemed at high leakage risk, limiting its effectiveness in preventing leakage and reducing global emissions (Campolmi et al., 2024).

objectives and with no announced phase-out dates (European Commission, 2025). As part of the *Clean Industrial Deal State Aid Framework*, the European Commission further eased the regulation for its member states to support energy-intensive firms as part of the clean energy transition (European Commission, 2025). In Germany, several industrial policies subsidizing fossil fuels exist, with spending amounting to roughly 1% of GDP in 2023. Most policies are tax exemptions with eligibility thresholds: only large, energy-intensive firms can apply for reductions in the standard tax on electricity and other fuels.

These policies, designed to protect firms from competitiveness losses, come at a substantial fiscal cost and introduce market distortions that undermine economic efficiency and climate objectives. Firms receiving energy tax exemptions have incentives to produce more energy-intensively and reduce their costs relative to competitors, thereby increasing their market share. Hence, tax exemptions cause within-firm misallocation toward greater energy consumption and across-firm misallocation toward more emissions-intensive producers. In a worst-case scenario, industrial policy could lead through domestic misallocation (Hsieh and Klenow, 2009) and a shift of global production from less emission-intensive foreign firms to more emissions-intensive German firms (Graevenitz et al., 2024) to an increase in global emissions or at least severely undermine a carbon tax. In an export-oriented economy, tax exemptions can be welfare-reducing through a fiscal distortion by subsidizing foreign consumption. Moreover, maintaining constant tax revenue requires the government to raise taxes in other areas, thereby creating additional distortions.

To provide new empirical insights into the extent of these tax exemptions and their consequences, I connect findings from EU data on state aid with energy price data by consumer size and German administrative data. The EU state aid database (Barone and Letta, Marco, 2021; Mulier et al., 2024) collects information on state aid recipients from all member states that exceed a reporting threshold, as well as the aggregate spending on these policies.

Spending on energy tax exemptions in Germany amounted to €35 billion in 2019, with the manufacturing sector being a major beneficiary. This spending is highly concentrated within and between sectors, primarily benefiting selected firms in EU ETS industries, the most energy-intensive sectors. Although the stated goal of these policies is to maintain international competitiveness and secure employment, neither export share nor employment levels determine aggregate spending patterns.

Due to tax exemptions, large energy consumers in Germany pay lower prices and are shielded from energy price increases. Compared to other countries, Germany has set relatively high taxes on energy, particularly electricity, resulting in the highest average price in the EU. Tax exemptions, primarily through the Renewable Energy Sources Act (EEG) surcharge exemption and partially reduced network charges, decrease the burden for qualifying firms and limit energy price increases for large consumers.

Using administrative data from the German manufacturing sector, I document that firms paying lower energy prices systematically differ from their peers along several key dimensions. These firms are, on average, larger, more energy-intensive, and more export-oriented. Although firm-level tax exemption data is not directly observable, the design of these exemptions, which primarily benefits large, energy-intensive consumers, likely accounts for part of this price dispersion. The resulting pattern of energy price differentials suggests that exemptions may distort production by favoring more energy-intensive firms, with implications for both allocative efficiency and the effectiveness of climate policy.

To rationalize these findings, I develop a model of exporting firms that use labor and energy to produce goods. Firms face firm-specific output and energy distortions. Introducing both output and energy distortions allows me to match the different correlations between emission intensity and firm size across industries and to understand how different distortions interact. To capture heterogeneity across and within sectors, I assume firms must first pay sector-specific fixed costs to learn about exemptions and then decide on the resources they invest in securing tax exemptions.[3]

Literature Review This paper aims to contribute to two different strands of the literature. First, I contribute to the literature on industrial policy and environmental outcomes. Governments frequently use grants, tax incentives, and other subsidies to influence firm behavior, productivity, and market structure. Rotemberg (2019) and Choi and Levchenko (2025) highlight that while subsidies can stimulate innovation, they often introduce allocative distortions across heterogeneous firms. In response to rising energy prices and carbon taxes in Germany, attention has focused on energy-specific tax exemptions. Gerster and Lamp (2024) demonstrates that energy-intensive firms benefit from tax exemptions, lowering electricity costs and increasing emissions. Similar patterns appear in other contexts: Jin et al. (2020) find that allowance allocation under China's emissions trading system affects firm competitiveness and abatement incentives. Fowlie et al. (2016) compare alternative policy designs to reduce emissions in an industry with market power, advocating for an optimal policy addressing import leakage via output-based free allocation or border tax adjustments. Conversely, Rentschler et al. (2017) show that fossil fuel subsidy reforms have heterogeneous effects on firms depending on their energy intensity. Recent contributions by Jo and Karydas (2024) and Casey et al. (2023) emphasize how subsidy schemes interact with firm heterogeneity and market structure to shape technology adoption, environmental outcomes, and competitiveness. Large-scale subsidy programs such as China's electric vehicle incentives and the US Inflation Reduction Act illustrate how environmental policy serves dual industrial and climate objectives, affecting firm investment, technology adoption, and export competitiveness (Dechezleprêtre and Sato, 2017; Gentile et al., 2025). Furthermore, firm political activity shapes these outcomes. Kang (2016) document how lobbying in the energy sector secures preferential regulatory treatment, while Meng and Rode (2019) estimate the social costs arising when such influence drives subsidy design. My contribution to this literature is twofold. First, I provide evidence on the prevalence and heterogeneity of tax exemptions across German manufacturing firms and industries. Second, I build a general equilibrium model to quantify the aggregate effects of energy tax exemptions on energy use, emissions, and exports.

Second, I contribute to the literature on resource misallocation across firms. Since Hsieh and Klenow (2009) demonstrated that allocative inefficiencies can reduce aggregate total factor productivity (TFP), subsequent work has extended this framework to capture fixed costs (Bento and Restuccia, 2017), enforcement frictions (Boehm and Oberfield, 2020), and sectoral productivity losses in general equilibrium (Baqaee and Farhi, 2020). Extensions to environmental contexts reveal that resource rents and carbon pricing amplify misallocation. Asker et al. (2019) and Monge-Naranjo et al. (2019) show how extraction constraints worsen allocation in resource sectors. Kim (2023) and Klenow et al. (2024), whose papers are closest to mine, focus on the interaction between existing distortions and a carbon tax introduction, jointly affecting emissions and productivity with firm heterogeneity in emission intensity. Additionally, Choi (2020) demonstrate empirically how distortions in energy and capital markets shape productivity outcomes. A growing strand also examines distortions with exporting firms. Berthou et al. (2019) and Bai et al. (2024) link trade barriers and liberalization to allocative efficiency,

[3]Since the mechanisms behind free allowances and energy tax exemptions are similar, the analysis can be easily extended to include free allowances as an additional source of heterogeneity in implicit energy prices.

while Choi (2025) highlight how lobbying can create distortions by shaping policy outcomes. I add to this literature by embedding endogenous export participation along the intensive margin and an emissions externality into the misallocation framework of Hsieh and Klenow (2009) and Choi (2025). This allows counterfactual exercises studying the joint impacts of selective energy-price exemptions on output, emissions, and firms' international competitiveness. Unlike most of the literature, with the exception of Kaymak and Schott (2024), I can quantify resource misallocation based on differential tax rates on energy inputs, enabling me to quantify both within-firm and between-firm misallocation effects of selective tax policies.

Section 3.2 describes the data and documents several stylized facts about energy tax exemptions. Section 3.3 outlines the structural model, while Section 3.4 outlines the planned direction of the paper. Section 3.5 concludes.

3.2 Descriptive Evidence

In this section, I begin by describing the data sources used in the analysis and provide information about the various energy-related tax exemptions in Germany. I then present several stylized facts on the prevalence of these exemptions within Germany's manufacturing sector and their relationship with industry- and firm-level economic outcomes.

3.2.1 Data

German Administrative Data I use administrative data ("Amtliche Firmendaten für Deutschland") provided by the Federal Statistical Office of Germany from 2011 to 2019. For my analysis, I combine several data sources. The primary dataset is the German manufacturing census at the firm level, with mandatory participation for all establishments with more than 20 employees. The data include information on sales, employment, investment, and sectoral affiliation. Additional information on value-added and expenditure on labor, energy, capital, and intermediate inputs is available for a representative sample of firms.

I combine this information with plant-level data on energy consumption, which contain information on consumption for 14 different fuel types and electricity in kilowatt-hours (kWh). Each fuel type and electricity can be matched to annual emission factors provided by the German Environmental Agency. I calculate total CO_2 emissions for each firm by multiplying energy consumption by its emission factor for each fuel type and summing across all energy types. Unless otherwise noted, I define emission intensity as emissions divided by firm sales.

Eurostat Energy Prices Based on electricity and gas price data reported by national statistical institutes, ministries, energy agencies, or system operators, Eurostat publishes annual price data for household and non-household consumers by consumption band starting in 2017.[4] For each consumption band, three broad price components are reported: energy and supply costs, network costs, and taxes.[5] For taxes, information on sub-components is available. See Appendix C.1 for further information on the data and price components.

[4] Households are divided into five consumption bands, and non-household consumers into seven bands.

[5] Bi-annual data exist starting in 2007, but information on price components is absent except for taxes.

EU State Aid Data The Directorate-General for Competition maintains a comprehensive database of public state aid cases notified by EU member states.[6] Since 1993, each case has been assigned a unique identifier and recorded with key variables, including the measure's start and end dates, official title, type of aid instrument, and annual expenditure. Via unique case identifiers, I can merge aggregate state aid data with beneficiary-level information.[7] Starting in 2016, EU transparency requirements for state aid mandate member states to provide information on large individual aid awards.[8] This dataset contains detailed information about the state aid itself, as well as information about the size, region, industry, and aid amount for each beneficiary. Additionally, each beneficiary is reported with its national identification number.

Based on these data, I classify exemptions into four broad categories:[9]

1. *Renewable Energy Sources Act (EEG) Surcharge Exemption*: This exemption applies to energy-intensive firms with annual electricity consumption exceeding 1 GWh and electricity costs representing at least 14% of gross value added. Its objective is to protect internationally exposed industries from disproportionate renewable levies while preserving a residual contribution to renewable energy financing. It covers grid-supplied electricity and reduces the EEG surcharge to a uniform rate of 0.05 ct/kWh from up to 6.88 ct/kWh in 2017.

2. *Energy Tax Exemption*: This exemption applies to manufacturing firms that use taxed energy products—such as mineral oil, natural gas, or coal—for process heat or as production inputs. Its objective is to support firms' competitiveness. It provides partial refunds of excise duties, subject to a minimum annual claim of €250.

3. *Electricity Tax Exemption*: This exemption applies to electricity-intensive firms. Its objective is to reduce electricity tax liabilities and to safeguard industrial competitiveness. It covers electricity drawn from the public grid. Before 2023, relief was granted at a fixed rate of 5.13 €/MWh, provided the annual relief amount exceeded €250.[10]

4. *Combined Heat and Power (CHP) Exemption*: This exemption applies to operators of (small) combined-heat-and-power installations with electrical output up to 2 MW whose self-generated electricity is consumed on-site. Its objective is to promote high-efficiency cogeneration and decentralized energy supply. It covers CHP-generated electricity and fully waives the electricity tax of 2.05 ct/kWh on self-consumption. Additionally, small and large firms are partially exempted from energy taxes on CHP fuels.

Among these four policies, only the combined heat and power generation exemption incentivizes firms to improve energy efficiency and reduce energy consumption. All other policies merely lessen the burden of high energy costs in Germany and subsidize fossil fuels, potentially incentivizing firms to underinvest in energy-saving technologies.

[6] The data are publicly accessible via the EU Open Data Portal: `https://competition-cases.ec.europa.eu/search`.

[7] The data are publicly accessible via the State Aid Transparency Search: `https://webgate.ec.europa.eu/competition/transparency/public/search/home/`.

[8] The threshold is €500,000.

[9] See Appendix C.1.3 for more details on the exemptions.

[10] The €250 base amount roughly corresponds to an annual electricity consumption of 50,000 kWh.

3.2.2 Stylized Facts

Fact 1 *Energy tax exemption spending is substantial and growing.*

Government expenditure on energy costs relief for firms represents a significant and expanding fiscal commitment. The total real value of tax exemptions rose from €29 billion to €33 billion between 2014 and 2021 (see Figure 3.1a). The majority of this expenditure consisted of full or partial reductions of the EEG surcharge, while the remaining three policy instruments collectively accounted for one-fifth of total spending. Following the abolition of the EEG surcharge in July 2022, related exemptions were discontinued, resulting in a subsequent decline in aggregate spending. Nevertheless, expenditure on other exemptions increased in 2022 and remains substantial. To contextualize the scale of these programs, in 2024, exemptions from the energy tax, electricity tax, and CHP levy together constituted Germany's largest category of state aid measures, totaling approximately €4.5 billion (BMF – Bundesministerium der Finanzen, 2023). Furthermore, in 2022, the energy cost containment policy, a €5 billion aid program, was introduced to protect firms from energy price increases resulting from the Ukraine-Russia conflict.

Figure 3.1b demonstrates that the increase in total spending is primarily driven by a growing number of firms applying for exemptions, particularly under the EEG surcharge and CHP schemes. Concurrently, the average aid amount per exemption has declined, suggesting that firms deriving smaller benefits from these policies have increasingly begun to participate over time. This pattern is consistent across all exemption categories. Energy-related tax exemption spending exhibits high sectoral concentration within the manufacturing sector. Among all firms receiving exemptions, 60% operate in manufacturing, followed by 30% in the energy sector. The remaining 10% are distributed equally between services and other industries (see Figure C.10 in the Appendix). This distribution reflects both these sectors' contributions to economic output and their aggregate energy consumption patterns. Manufacturing firms, which rely heavily on energy inputs and face international competitive pressures due to their export dependence, constitute the primary beneficiaries of these policies.[11] Consequently, the remainder of this paper focuses exclusively on the manufacturing sector.

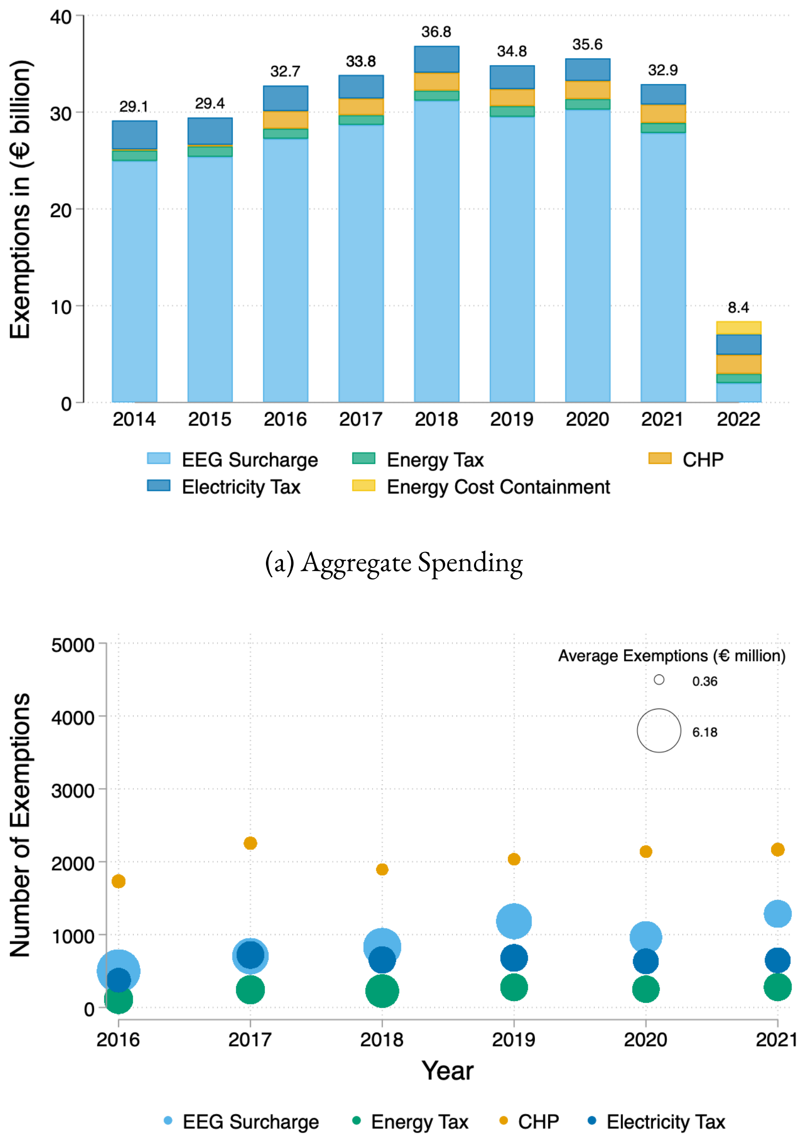
Fact 2 *Tax exemptions are concentrated within energy-intensive industries.*

Energy-related tax exemptions within the manufacturing sector exhibit high concentration among a limited number of industries, predominantly those covered by the EU ETS. Figure 3.2 presents the distribution of these exemptions across two-digit manufacturing industries in Germany for 2019, distinguishing between EU ETS and non-EU ETS industries. Panel (a) displays each industry's share of the total number of exemptions, while Panel (b) shows the corresponding share of the total exemption value.

In both dimensions, the distribution is heavily skewed: EU ETS industries collectively account for more than half of the firms receiving exemptions and more than 70% of the total value granted, despite representing only 20% of all industries. Moreover, the concentration of energy-related tax exemptions across industries has increased over time. Notably, the distribution of firms and exemption values is not perfectly aligned. Plants in the coke and refined petroleum products (19) and chemicals (20) industries, both covered by the EU ETS, receive substantially higher average exemptions. Conversely, plants in the manufacturing of metal products (25) exhibit the opposite pattern. The misalignment between the extensive and

[11] Manufacturing firms may also benefit indirectly from exemptions granted to the energy sector if cost reductions are transmitted through lower electricity prices.

Figure 3.1: Energy Tax Exemptions in Germany

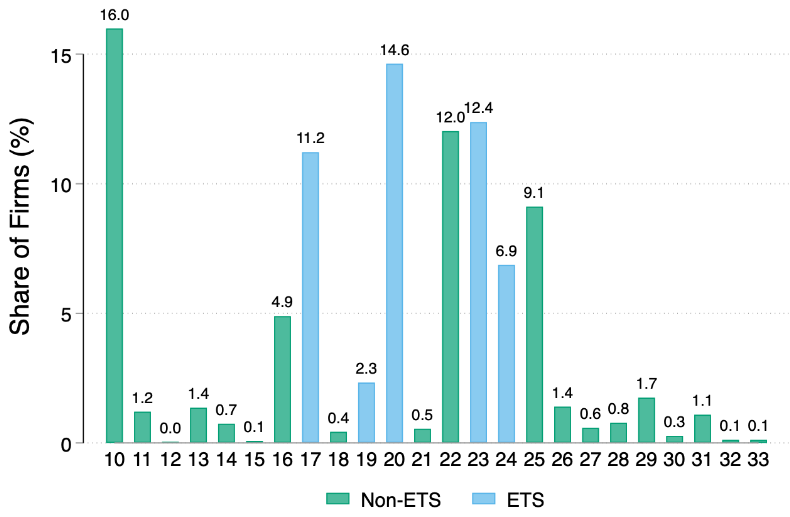


(a) Aggregate Spending

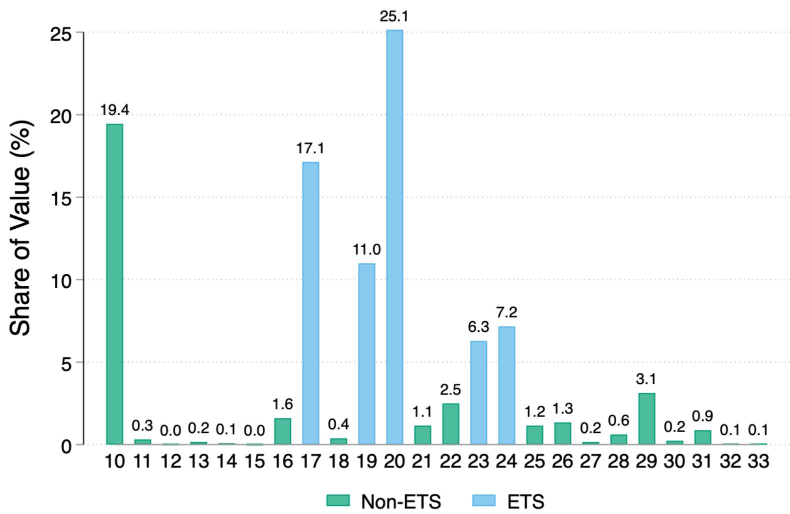
(b) Extensive and Intensive Margin

Notes: This figure presents information on energy-related tax exemptions in Germany. Panel (a) displays annual expenditure on exemptions by category from 2014 to 2022, measured in billion EUR (2015 prices). Panel (b) shows the number of exemptions granted (extensive margin) and the average exemption amount (intensive margin, in million EUR, 2015 prices) between 2016 and 2021, disaggregated by exemption type. The size of each bubble represents the average exemption amount. Exemptions are classified into four categories: EEG surcharge, energy tax, CHP levy, and electricity tax. These exemptions apply to non-household consumers across various sectors. For details on the classification of policies into exemption categories, see Appendix C.1.3.
Source: EU State Aid Transparency Database.

Figure 3.2: Tax Exemptions by Industry



(a) Share of Plants



(b) Share of Expenditure

Notes: This figure shows the distribution of energy-related tax exemptions across manufacturing industries in Germany in 2019. Panel (a) shows the share of plants receiving tax exemptions by industry. Panel (b) displays the share of the total value of exemptions in billion EUR (2015 prices) by industry. Tax exemption values in Panel (b) are based on plant-level data for 2019, with plants assigned the midpoint of their tax exemption bracket. Industries are categorized as either participating in the EU ETS or not. ETS industries include NACE codes 17 (Paper and paper products), 19 (Coke and refined petroleum products), 20 (Chemicals and chemical products), 23 (Other non-metallic mineral products), and 24 (Basic metals).
Source: EU State Aid Transparency Database.

intensive margins reflects differences in the composition of tax exemptions. A relatively higher share of plants in EU ETS industries receive EEG surcharge, electricity tax, or energy tax exemptions, which have higher average exemption values.

Examining the share of total exemptions and total value allocated to each industry does not account for heterogeneity in industry size or other relevant factors. Therefore, to analyze the drivers of exemption distribution across industries in greater detail, I merge the exemption data with industry-level statistics on employment, sales, and exports from the German Statistical Office for 2016- 2023. While industries' energy intensity, proxied by their EU ETS status, naturally serves as a strong predictor of the likelihood of receiving energy-related tax exemptions, the underlying policy objective is to safeguard firms' international competitiveness and, by extension, protect employment.

To analyze the determinants of the number of firms receiving exemptions, I estimate the following regression model using a Poisson Pseudo-Maximum Likelihood (PPML) estimator:[12]

$$\begin{aligned} Y_{it} = \exp\Big(&\beta_1 \text{ETS}_i + \beta_2 \text{Sales}_{it} + \beta_3 \text{ExportShare}_{it} \\ &+ \beta_4 \text{Workers}_{it} + \beta_5 \text{Plants}_{it} + \delta_t\Big)\, \varepsilon_{it}. \end{aligned} \tag{3.1}$$

where Y_{it} is the number of firms receiving tax exemptions in industry i and year t, ETS_i is a dummy variable indicating whether industry i is covered by the EU ETS, $Sales_{it}$ represents sales volume, $ExportShare_{it}$ is the ratio of exports to sales, $Workers_{it}$ denotes the number of employees, $Plants_{it}$ controls for the number of plants, and δ_t represents year fixed effects.

Columns (1) - (4) of Table 3.1 demonstrate that the EU ETS dummy is positive and significant across different specifications, including additional controls, confirming that energy-intensive industries subject to the EU ETS are more likely to benefit from exemptions. Similarly, industry sales exhibit a large positive and significant effect. Despite the stated objective of maintaining international competitiveness through tax exemptions, the export share exhibits no statistically significant correlation with, implying limited correlation between energy intensity and export activity at the industry level. Employment exhibits a strong negative and significant correlation, which is inconsistent with the policy objective of safeguarding jobs. Instead, the policies favor industries with high value-added per worker. These results demonstrate that a combination of energy intensity, production scale, and labor intensity, primarily drives the extensive margin of tax exemptions at the industry level.

Next, I examine the determinants of total exemption value. I employ the following regression model estimated via OLS:

$$\begin{aligned} Y_{it} = &\beta_1 \text{ETS}_i + \beta_2 \text{Sales}_{it} + \beta_3 \text{ExportShare}_{it} \\ &+ \beta_4 \text{Workers}_{it} + \beta_5 \text{Plants}_{it} + \delta_t + \varepsilon_{it}. \end{aligned} \tag{3.2}$$

where Y_{it} is the total tax exemption volume received by firms in industry i and year t. The explanatory variables and fixed effects remain identical to those in the previous regression for the number of tax exemptions.

Columns (5) - (8) of Table 3.1 show that the EU ETS dummy remains positive and statistically significant, indicating that energy-intensive industries receive larger aggregate tax

[12]The PPML estimator better accommodates the count nature of the dependent variable, including industries without any firms receiving tax exemptions, compared to a standard OLS estimator.

exemptions. Sales and export share coefficients are positive but not statistically significant across specifications, again suggesting limited explanatory power once energy intensity is controlled for. Employment does not exhibit a statistically significant effect on total exemption volume. This pattern suggests that while industry energy intensity strongly influences both the extensive (number of firms) and intensive (total exemption value) margins of exemptions at the industry level, labor intensity and sales predominantly affect the extensive margin.

Overall, the explanatory power of industry characteristics beyond energy intensity on the extensive and intensive margins of tax exemptions remains limited. The increase in the regression's R^2 after adding sales, export share, and workers from 0.51 to 0.58 is modest, and a substantial portion of the variation remains unexplained. However, the heterogeneity across industries, attributable to differences in energy intensity, remains considerable.

Fact 3 *Tax exemption status and value vary across firms within the same sector.*

In addition to substantial heterogeneity in tax exemptions across industries, considerable variation exists within industries. Figure 3.3a shows that the proportion of plants exempt from energy-related taxes varies significantly across sectors. On average, EU ETS industries exhibit a higher share of exempted plants, with the coke and refined petroleum products industry (NACE code 19) demonstrating the highest exemption rate. Differences in exemption shares are influenced primarily by two factors: the energy intensity of production and the volume of fuel consumed. Consequently, even plants with low energy intensity may qualify for exemptions if their scale of production is sufficiently large, which accounts for the relatively high exemption rates observed in some non-EU ETS industries. It is important to note that the EU's minimum reporting requirement for state aid can bias these results, particularly for less energy-intensive industries. Therefore, the reported figures should be regarded as lower-bound estimates for these sectors.

Figure 3.3b reveals substantial heterogeneity in exemption values among firms within industries. On average, firms in ETS-regulated sectors receive higher exemption amounts, with a less concentrated distribution compared to those outside the EU ETS. Nonetheless, some non-ETS firms also obtain sizable exemptions. Due to the absence of firm-level energy consumption and sales data, it remains unclear whether this dispersion reflects scale effects or differences in treatment intensity arising from policy-specific eligibility thresholds that permit some firms to combine multiple exemptions.[13]

Fact 4 *Tax exemptions substantially contribute to energy price heterogeneity.*

Tax exemptions on energy prices result in lower energy prices and are a major contributor to energy price heterogeneity in Germany.[14] While energy-related tax exemptions apply to different fuel types, electricity receives the highest tax reductions. Moreover, electricity accounts for roughly half of all fuel consumption. Hence, I will focus mostly on the effect of tax exemptions on electricity prices.

Several insights emerge from Figure 3.4a. First, electricity prices vary substantially across consumption bands: firms in the smallest consumption band pay approximately twice as much

[13]The only firm-level information available in the data is the classification of firms into large firms and small and medium enterprises (SMEs), based on the number of workers. SMEs, defined as firms with fewer than 250 workers, are less likely to receive exemptions and, on average, receive lower exemption amounts (see Figure C.12a and Figure C.12b). Figure C.11 shows that SMEs are most likely to receive a CHP exemption.

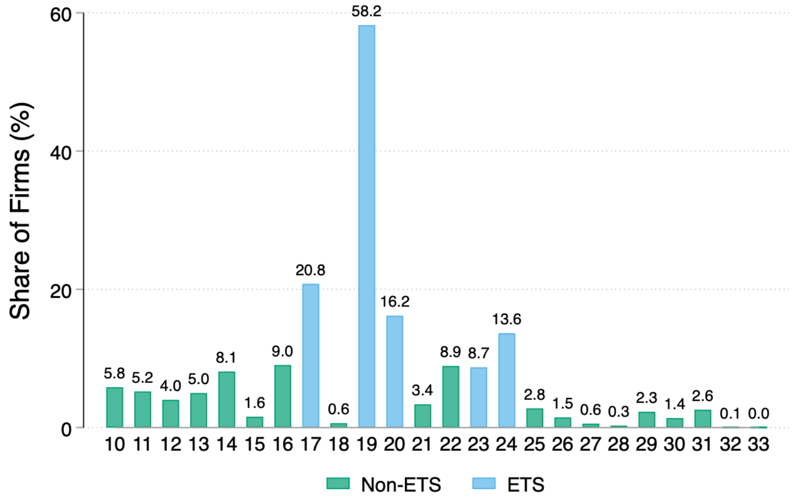
[14]A similar pattern can be observed for other EU countries, both in terms of electricity and gas prices. See Appendix C.3.2 for more detailed evidence.

Table 3.1: Determinants of Tax Exemptions

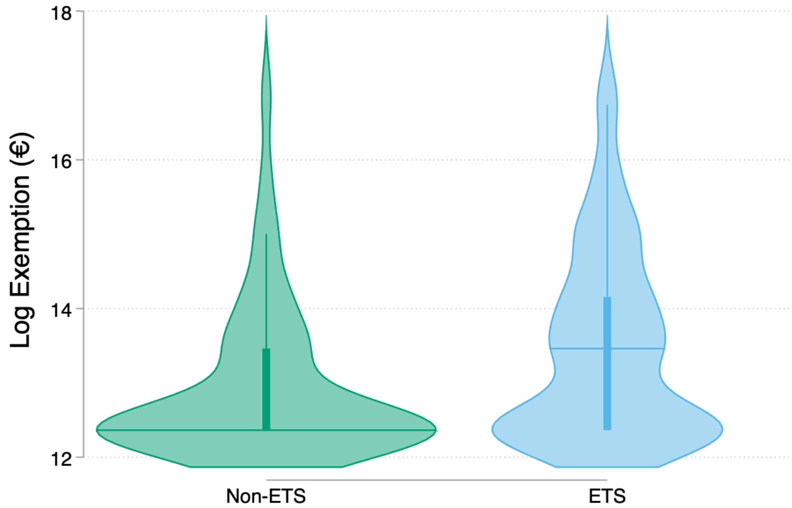
	Number of Exemptions – PPML				Exemption Volume – OLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dummy ETS	1.8570***	1.8702***	1.8579***	1.4721***	0.4867***	0.4765***	0.4808***	0.4319***
	(0.3192)	(0.3252)	(0.3476)	(0.3177)	(0.1624)	(0.1520)	(0.1562)	(0.1485)
Sales		0.8447	1.8065	13.7768***		0.6007	0.5038	2.1645
		(2.1303)	(2.2977)	(3.7074)		(0.3966)	(0.3757)	(1.3678)
Export Share			-0.6736	1.4641			0.0889	0.2757
			(1.3862)	(1.1217)			(0.2588)	(0.2569)
Workers				-6.9944***				-0.9476
				(1.8617)				(0.6297)
Year FE	✓	✓	✓	✓	✓	✓	✓	✓
# Plants	✓	✓	✓	✓	✓	✓	✓	✓
Observations	192	192	192	192	192	192	192	192
R^2	-	-	-	-	0.513	0.544	0.546	0.576

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. This table presents regression results analyzing the industry-level determinants of exemption outcomes from 2016 to 2023, using a balanced panel of manufacturing industries. The dependent variables are the number of exempted plants (columns 1–4, estimated via PPML) and total expenditure on exemptions in billion 2015 euros (columns 5–8, estimated via OLS). Dummy ETS is a binary indicator denoting whether an industry is subject to the EU ETS. Sales are measured in billion 2015 euros, workers in millions, and export share as the ratio of exports to sales. All models include year fixed effects. Robust standard errors clustered at the industry level are reported in parentheses.
Source: EU State Aid Transparency Database and the German Statistical Office.

Figure 3.3: Distribution of Tax Exemptions Across Industries



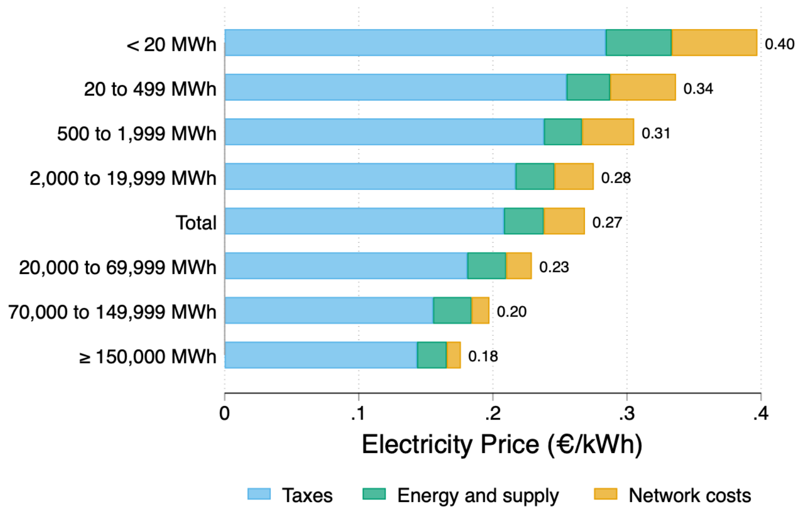
(a) Share of Exempted Plants



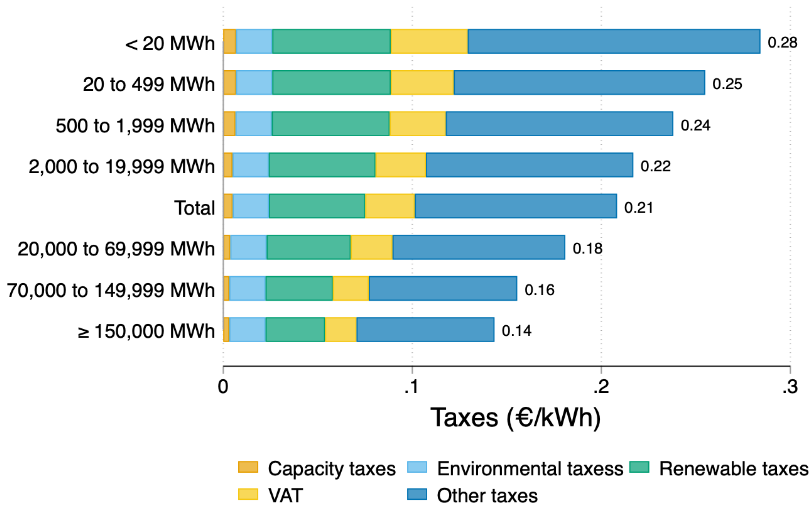
(b) Distribution of Expenditure

Notes: This figure presents the distribution of energy-related tax exemptions in Germany in 2019, by industry. Panel (a) displays the share of plants receiving exemptions (extensive margin), calculated by dividing the number of exempted plants by the total number of plants in each industry. Panel (b) depicts the distribution of exemption expenditure in million EUR (2015 prices) within ETS and non-ETS industries. Expenditure amounts are based on plant-level data, with plants assigned the midpoint of their tax exemption brackets. Industries are categorized as either participating in the EU ETS or not. ETS industries include NACE codes 17 (Paper and paper products), 19 (Coke and refined petroleum products), 20 (Chemicals and chemical products), 23 (Other non-metallic mineral products), and 24 (Basic metals).
Source: EU State Aid Transparency Database and the German Statistical Office.

Figure 3.4: Electricity Price Components by Consumption Band



(a) Price Components



(b) Tax Components

Notes: This figure shows the composition of electricity prices for industrial consumers in Germany in 2019 across various consumption bands. The electricity price is measured in €/kWh. Panel (a) disaggregates prices into three components: energy and supply costs, network costs, and taxes. Panel (b) further breaks down the tax component into capacity taxes, environmental taxes, renewable taxes, VAT, and other taxes. Industrial consumers are segmented into seven consumption bands, ranging from less than 20 MWh to 150,000 MWh or more. A total consumption category represents the average price for all industrial consumers.
Source: Eurostat's electricity price components statistics.

as those in the largest.[15] Second, the high electricity price in Germany is driven predominantly by taxes rather than energy or network costs. Taxes account for two-thirds of the average consumer's electricity bill. Third, this heterogeneity is primarily attributable to differences in the tax component, with network costs contributing to a lesser extent. In contrast, energy and supply costs remain relatively stable across consumption bands. Without the detailed insights into the cost components, an alternative explanation for electricity price dispersion could have been the input market power of large firms. Even though large firms pay only half the energy costs, the contribution of energy and supply costs to lower energy prices is the smallest across all three components.

What is driving the heterogeneity in taxes and network costs across consumption bands? Evidence from the previous facts suggests that exemptions for large consumers could help lessen their burden of high energy costs through taxes. Assuming that the exemptions are truly the driver behind the heterogeneity in taxes, this implies that the heterogeneity in the value of tax exemptions is not only driven by scale effects but also by differences in the treatment intensity.

Figure 3.4b disaggregates taxes into five categories: capacity taxes, environmental taxes, renewable taxes, VAT, and other taxes. The *other taxes* category aggregates all remaining charges, fees, levies, and network charges, which constitute most of this category. Most heterogeneity stems from variation in the renewable tax and other tax components. VAT differences across consumption bands reflect variation in all underlying price components, as VAT is charged on the aggregate price, thereby amplifying disparities.

The heterogeneity in the renewable tax largely stems from the EEG surcharge exemption, which provides relief to firms that consume over 1 GWh annually. This mechanism can be empirically identified by examining consumption patterns around the exemption threshold. Conversely, the electricity tax exemption, which affects the capacity tax, has a comparatively minor effect on tax heterogeneity due to its low rate (0.2 ct/kWh). Variations in other taxes primarily reflect spatial differences (Graevenitz and Rottner, 2024) and exemptions from network charges under §§ 19 Abs. 2 Satz 1 and 2 StromNEV. These exemptions are not subject to EU state aid reporting, so systematic data on their monetary value is unavailable. Only lists of exempted plants published by the Bundesnetzagentur (Federal Network Agency) are accessible. In 2019, 240 exemptions were granted under § 19 Abs. 2 Satz 1 and 839 under § 19 Abs. 2 Satz 2. For comparison, 5,775 exemptions for the four other relevant policies were recorded above the EU reporting threshold that year.

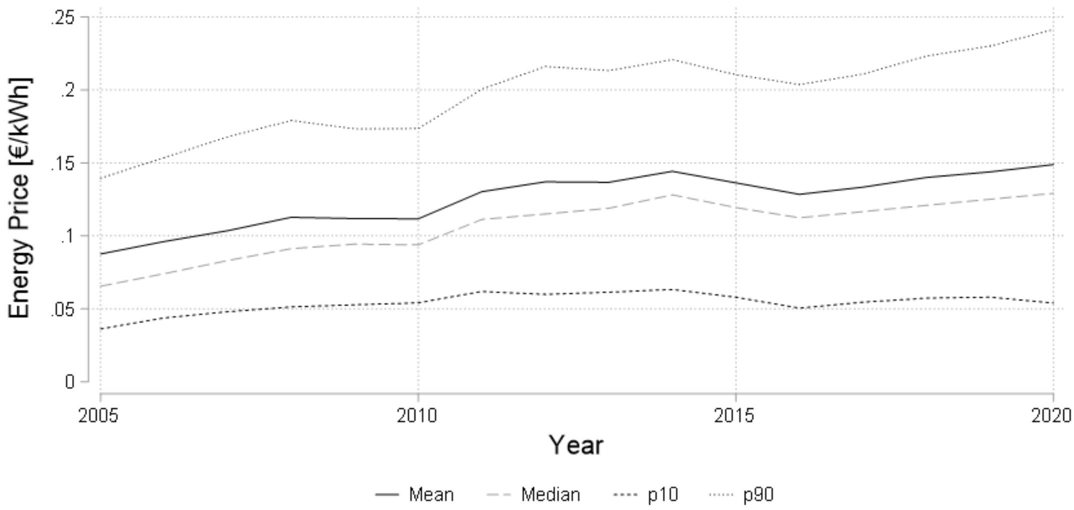
Fact 5 *Tax exemptions protect large firms from energy price increases.*

Large energy consumers not only pay lower prices but are also shielded from energy price increases. Figure 3.5 presents data from German administrative data on manufacturing firms, indicating that between 2005 and 2020, the mean and median energy prices increased by approximately 50%. However, prices faced by firms in the 90th percentile increased by approximately 66%, while those in the 10th percentile experienced only a modest increase of 25%.

What drives the divergence in electricity prices across firms? To investigate this question, I draw on electricity price data disaggregated by firm size, which includes detailed information on the different price components. First, these data reveal that the aggregate price trends by firm size closely mirror the patterns observed in firm-level energy price data when focusing on the comparable medium and large firms (see Figure C.2a in the Appendix). This group

[15] Davis et al. (2013) find a similar spread in electricity prices within the United States.

Figure 3.5: Trends in Energy Prices for German Manufacturing Firms



Notes: This figure displays the annual mean, median, 10th percentile (P10), and 90th percentile (P90) of energy prices (€/kWh) for German manufacturing firms between 2005 and 2020. Energy prices are computed by dividing total energy expenditure in euros by total energy consumption in kilowatt-hours, including both fuels and electricity. All nominal values are deflated to constant 2015 prices.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

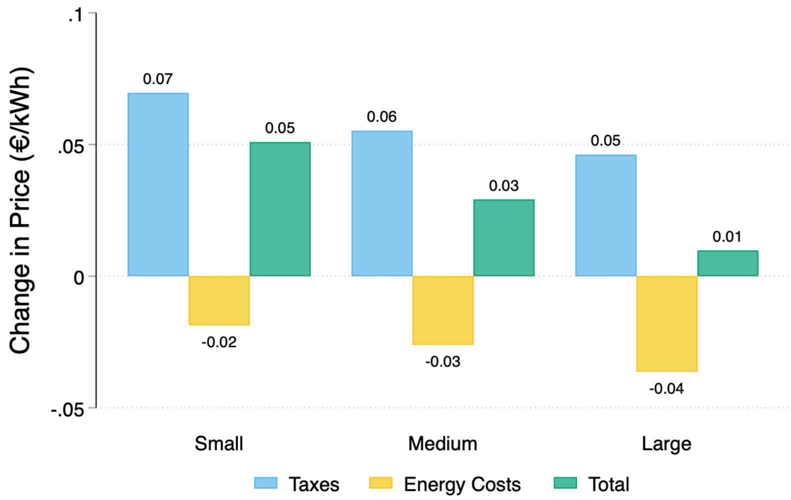
is roughly equivalent to the electricity consumption of firms sampled in the administrative data. Moreover, these groups of firms are also eligible to apply for exemptions from the EEG surcharge and the electricity tax.

To identify the sources of these differences, Figure 3.6a decomposes the absolute aggregate change in electricity prices between 2008 and 2020 into changes in energy costs and taxes and levies. The decomposition shows that rising taxes primarily drove the overall increase, while energy costs declined over the same period. However, the decrease in energy costs was insufficient to offset the rise in taxes, resulting in a net price increase. Notably, these dynamics varied systematically by firm size: smaller firms experienced both a larger increase in tax components and a smaller decrease in energy costs compared to larger firms. As a result, the rise in electricity prices was more pronounced for smaller firms.

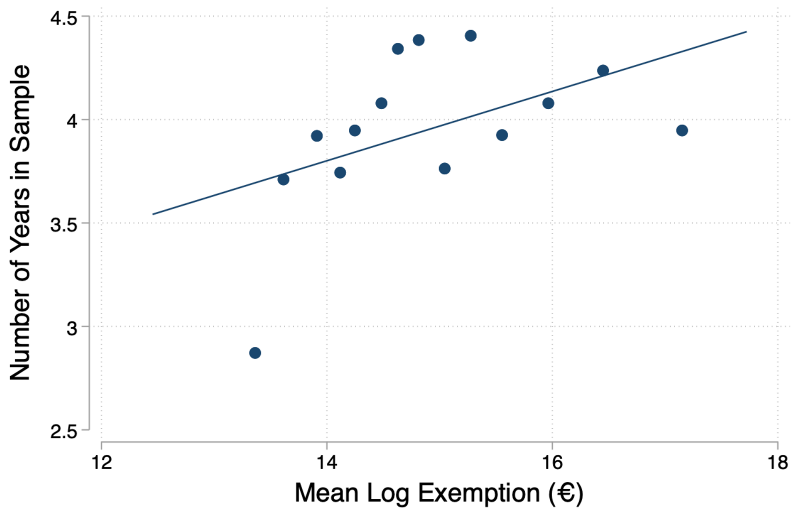
One of the main drivers of this heterogeneity is eligibility for EEG surcharge exemptions. While the surcharge increased considerably over the period, larger electricity consumers were more likely to qualify for substantial reductions, mitigating their tax burden. Figure 3.6b corroborates this mechanism, showing that firms benefiting from large exemptions typically remained exempt throughout the sample period. However, note that the EU Transparency database of exempt firms overrepresents larger firms, so the observed trend primarily reflects firms receiving substantial exemptions.[16] These persistent exemptions not only reduce current energy costs for large firms but also shape their future energy consumption patterns. By shielding firms from rising electricity prices, exemptions can generate a lock-in effect (Fouquet,

[16]Figure C.13 provides evidence on the persistence of exemptions along the intensive margin.

Figure 3.6: Tax Exemptions and Electricity Price Changes



(a) Electricity Price Change Decomposition



(b) Persistence Exemptions

Notes: Panel (a) reports a decomposition of the change in electricity prices for industrial consumers in Germany between 2007 and 2020, expressed in constant 2015 €/kWh, for different consumption bands. Prices are disaggregated into two components: Energy Costs and Taxes. The sum of these components equals the total aggregate price change, which is also reported. Consumption bands are defined as follows: small firms (MWh 500–1,999), medium firms (MWh 20,000–69,999), and large firms (MWh 70,000–149,999). Data are obtained from Eurostat's electricity price statistics. Panel (b) displays the unconditional correlation between the average annual value of exemptions received (expressed in 2015 €) and the number of years a firm benefited from exemptions between 2016 and 2021. Exemptions refer to relief from the EEG surcharge and the electricity tax.
Source: EU State Aid Transparency Database and Eurostat's electricity price statistics.

2016; Hawkins-Pierot and Wagner, 2024), biasing technological change toward energy-intensive technologies.

A similar, though less pronounced, pattern emerges for gas prices. Prices differ substantially across consumption bands, with larger firms consistently paying less. Unlike electricity, however, gas pricing involves considerable variation across all three components of the final price – energy costs, network charges, and taxes – with the tax share much smaller than for electricity (see Figure C.3a). As a result, the divergence in gas prices between small and large firms is less driven by tax exemptions and more by differences in energy costs (see Figure C.4a). Notably, gas prices declined for all firm categories over the period, a trend that may help explain an additional mechanism highlighted by Graevenitz and Rottner (2024): large firms increasingly substituted grid-supplied electricity for on-site generation to mitigate their exposure to rising electricity prices further.

Fact 6 *Low-energy-price firms are larger, more energy- and export-intensive.*

Energy prices are systematically correlated with other firm-level characteristics. While I cannot directly observe which firms receive tax exemptions in the microdata, firm-level energy prices are systematically correlated with other characteristics. The evidence indicates that firms paying lower energy prices differ along several important dimensions.

As shown in Figure 3.7a, these firms are, on average, larger in terms of sales, consistent with the structure of tax exemptions primarily benefiting large consumers. Moreover, in line with the stated policy objective of supporting international competitiveness, Figure 3.7b demonstrates a negative correlation between energy prices and export shares: firms with lower energy prices tend to have higher export intensities. In addition, Figure 3.7c reveals that firms facing lower energy prices are, on average, more energy-intensive.[17]

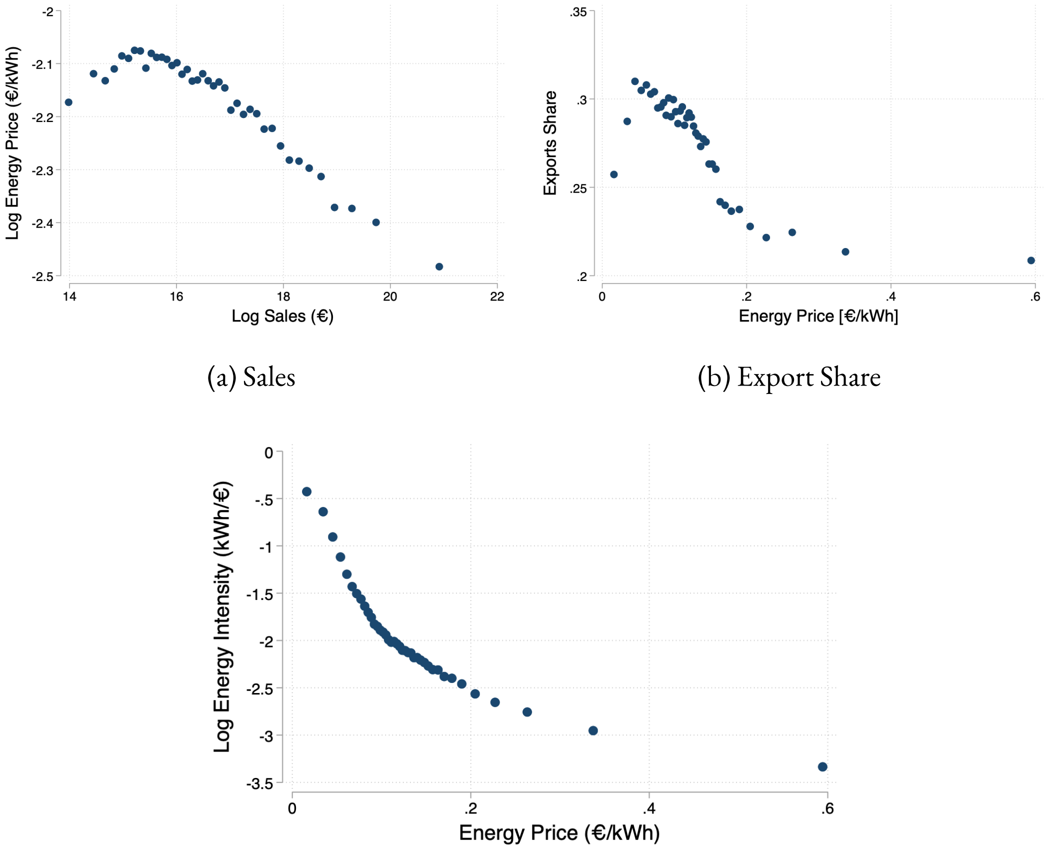
These patterns suggest that exemptions disproportionately favor firms with higher energy consumption per unit of output, potentially contributing to a reallocation of economic activity toward more energy- and emission-intensive production. Such reallocation can increase the average energy and emission intensity of aggregate manufacturing output, with implications for both efficiency and climate policy. Since these firms are also larger and more likely to engage in international trade, the observed correlations are consistent with broader patterns of firm heterogeneity known to affect market power, markups, and resource misallocation.

Summary Expenditure on energy tax exemptions in Germany has grown steadily over the past decade, and the benefits remain highly concentrated among a small number of firms. These beneficiaries are typically larger, more energy- and emission-intensive, and predominantly active in sectors covered by the EU ETS. Exemption eligibility is determined by plant-level thresholds, concentrating both tax exemptions and associated fiscal costs within energy-intensive industries that contribute relatively little to aggregate sales, employment, and exports.

This allocation pattern has important implications for energy and climate policy. Tax exemptions risk distorting production by reallocating output both across and within sectors, disproportionately favoring firms with higher energy intensities. The potential for misallocation of production toward less energy-efficient firms may not only raise aggregate emissions but also reduce allocative efficiency and increase market power. Tax exemptions can also skew the export mix toward more emissions-intensive industries if similar policies are absent in

[17] subsection C.3.4 shows that firms with low energy prices not only have a higher export share but also higher total exports. Additionally, it provides the regression tables corresponding to the binscatter plots, including additional regressors.

Figure 3.7: Energy Prices and Firm Outcomes



(a) Sales

(b) Export Share

(c) Energy Intensity

Notes: This figure shows three binscatter plots examining the relationships between firm-level energy prices and firm outcomes using German administrative data for the manufacturing sector from 2011 to 2018. Panels (a) and (b) depict log(energy price) as the dependent variable, with log(sales) and export share as the independent variables, respectively. Panel (c) reverses this relationship, showing log(energy intensity) as the dependent variable and log(energy price) as the independent variable. All regressions control for four-digit industry and year fixed effects. Observations are divided into equally sized bins based on the independent variable, with means of both variables calculated within each bin. Dependent variables are residualized to account for fixed effects. Energy intensity is defined as the ratio of the firm's fuel and electricity consumption to its sales. The energy price is calculated by dividing the total energy expenditure by the total energy consumption in kilowatt-hours, including electricity. The export share is defined as exports divided by total sales. All nominal values are deflated to constant 2015 prices.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

other countries — a concern consistent with the findings of Graevenitz et al. (2024). From an environmental perspective, exemptions weaken the carbon price signal embedded in the EU ETS by lowering marginal energy costs for firms already subject to emissions trading, encouraging more energy-intensive production, and distorting efficient abatement incentives.

While reduced-form evidence consistently reveals correlations between energy prices and firm characteristics, it cannot capture the general equilibrium effects of exemptions on aggregate outcomes such as sales, emissions, and exports. To address this limitation, I develop a structural model that quantifies these effects and accounts for adjustments along both the intensive and extensive production margins.

3.3 Model

This section introduces a heterogeneous firms model with monopolistic competition, firm-specific distortions, and productivity differences to study the effects of misallocation on aggregate output, emissions, and exports. The model closely follows Hsieh and Klenow (2009) and Choi (2025), combining their frameworks and incorporating energy as an additional production factor subject to distortions.

3.3.1 Environment

Firms live in a large, open economy, produce differentiated varieties, and compete monopolistically. There exists a second country, called Foreign, which differs from Home in its endowments and the primitive distribution of its firms. A representative consumer is endowed with L units of labor and maximizes their utility subject to the budget constraint: $PC = wL + \Pi + T$. Furthermore, I assume that the supply of labor is inelastic. In contrast, the supply of energy is perfectly elastic, and one unit of energy can be purchased at an exogenous price of p_E.

Consumer preferences I model the preferences of a representative agent as a two-tier utility function. The aggregate output good is a Cobb-Douglas composite of sectoral output Y_s:

$$U = \prod_{s=1}^{S} Y_s^{\beta_s}, \tag{3.3}$$

where $\beta_s \in (0,1)$, with $\sum_{s=1}^{S} \beta_s = 1$, are constant expenditure shares. There exists one non-tradable, outside sector.

Within each sector s, a perfectly competitive firm assembles a CES aggregate of the domestic varieties produced by firms within the sector:

$$Y_s = \left[\int_{\omega_s \in \Omega_s} Y_s(\omega_s)^{\frac{\sigma_s - 1}{\sigma_s}} d\omega_s \right]^{\frac{\sigma_s}{\sigma_s - 1}}, \tag{3.4}$$

where $\sigma_s > 1$ represents the sector-specific elasticity of substitution. Each sector of the economy is populated by a set of heterogeneous firms denoted by Ω_s. Each firm produces a different variety indexed by ω_s. In the following, I replace ω_s with the index i and treat the number of firms Ω_s within each sector as fixed.

Production Firms employ two factors of production: labor L_{si}, and energy E_{si}. The production function is given by the following Cobb-Douglas function:[18]

$$Y_{si} = A_{si} E_{si}^{1-\alpha_s} L_{si}^{\alpha_s}, \tag{3.5}$$

where A_{si} is a Hicks-neutral productivity. Emissions are a by-product of production and can be computed by multiplying the energy input E_{si} of a firm by a constant emission factor ν_{si}.

Demand for firm i's variety is given by:

$$q_{si} = p_{si}^{-\sigma_s} P_s^{1-\sigma_s} S_s, \tag{3.6}$$

where $P_s = \left(\int p_{si}^{1-\sigma}\, di\right)^{\frac{1}{1-\sigma}}$ is the aggregate price index for sector s and S_s is the aggregate spending on the sector s composite good.

3.3.2 Distortions

Firms face two types of distortions: an output distortion $\tau_{Y_{si}}$, which affects the marginal product of all input factors equally, and an energy distortion $\tau_{E_{si}}$. For example, firms without access to cheap energy due to the absence of tax exemptions face a higher $\tau_{E_{si}}$, increasing their marginal cost of energy. Similarly, firms subject to higher output taxes face a higher $\tau_{Y_{si}}$. For simplicity, I assume that the output distortion $\tau_{Y_{si}}$ is exogenously given. In contrast, the energy distortion $\tau_{E_{si}}$ consists of both an endogenous and an exogenous component, depending on firm resources t_{si} devoted to securing tax exemptions:

$$\tau_{E_{si}} = \begin{cases} \tau_{Esi} t_{si}^{\theta} & \text{if } t_{si} > 0 \\ \tau_{Esi} & \text{if } t_{si} = 0 \end{cases} \tag{3.7}$$

τ_{Esi} is the exogenous distortion drawn from a given distribution, accounting for variation in energy prices that is not governed by taxes, i.e., the location of a firm or its fuel mix. The parameter θ governs the sensitivity of the distortions with respect to the effort of obtaining tax exemptions.[19] In addition to the variable costs, firms have to pay a fixed cost f_{st} to select into receiving tax exemptions. The fixed costs can be interpreted as an information cost, required for firms to inform themselves of the available tax exemptions. Both the variable and fixed costs for tax exemptions are expressed in labor. Introducing both fixed and variable costs to obtain tax exemptions rationalizes the extensive and intensive margin effects observed in the data. Only some firms obtain tax exemptions, and among the firms receiving tax exemptions, their effective tax rate on energy varies. I assume that the government collects the revenue from the distortions. Tax revenue is rebated to the consumers via a lump-sum transfer.

[18]This can be easily extended to a CES production function to introduce an elasticity of substitution that is different from one.

[19]One can think of θ as reflecting the government's choice of the reduced tax rate.

3.3.3 Firm Problem

Pricing and Exporting Since consumer preferences are CES, the price of a firm, p_{si}, equals its unit costs multiplied by a constant markup $\frac{\sigma_s}{\sigma_s - 1}$:

$$p_{si} = \underbrace{\frac{\sigma_s}{\sigma_s - 1}}_{\text{markup}} \underbrace{\left(\frac{w}{\alpha_s}\right)^{\alpha_s} \left(\frac{p_E}{1-\alpha_s}\right)^{1-\alpha_s} \left(\frac{(1+\tau_{E_{si}})^{1-\alpha_s} \tau_C^{1-\alpha_s}}{A_{si}(1-\tau_{Y_{si}})}\right)}_{\text{unit costs}}, \tag{3.8}$$

where τ_C is a carbon tax, the revenue of which is rebated as a lump-sum transfer to the consumers. $\tau_{Y_{si}}$ and $\tau_{E_{si}}$ are distortions.
Firms can export after paying a fixed costs F_X in terms of labor.[20] The demand of Foreign j is given by:

$$Y_{sij} = p_{sij}^{-\sigma_s} b_j, \tag{3.9}$$

where $p_{sij} = (1 + \tau_x) p_{si}$ is the price of variety si in market j and b_j captures the size of market j. $\tau_x > 1$ is an iceberg trade cost.
Firms select into exporting if their variable profits exceed the fixed costs of exporting:

$$\pi_{sij}^v = \sigma^{-\sigma}(\sigma - 1)^{\sigma-1}(1 + \tau_x)^{1-\sigma} u_{si}^{1-\sigma} > w F_X. \tag{3.10}$$

Profit Maximization The firm maximizes its profits by jointly deciding on its export status and whether to obtain tax exemptions:

$$\begin{aligned}
\pi_{si} = \max_{b,x} \Bigg\{ & \Bigg\{ (\tau_{Es} t_{si}^{\theta})^{\sigma} u^{1-\sigma} \times B + (\tau_{Es} t_{si}^{\theta})^{\sigma} u^{1-\sigma} (1+\tau_x)^{1-\sigma} \times b_j \\
& - w(f_x + f_{st}) \Bigg\} \cdot \mathbf{1}[t_{si} > 0, x = 1] \\
& + \Bigg\{ (\tau_{Es} t_{si}^{\theta})^{\sigma} u^{1-\sigma} \times B - w f_{st} \Bigg\} \cdot \mathbf{1}[t_{si} > 0, x = 0] \\
& + \Bigg\{ {\tau_{Es}}^{\sigma} u^{1-\sigma} \times B + {\tau_{Es}}^{\sigma} u^{1-\sigma} (1+\tau_x)^{1-\sigma} \times b_j \\
& - w f_x \Bigg\} \cdot \mathbf{1}[t_{si} = 0, x = 1] \\
& + \Bigg\{ {\tau_{Es}}^{\sigma} u^{1-\sigma} \times B \Bigg\} \cdot \mathbf{1}[t_{si} = 0, x = 0] \Bigg\},
\end{aligned} \tag{3.11}$$

where $B = P_s^{1-\sigma} S_s \sigma^{-\sigma} (\sigma - 1)^{\sigma - 1}$ and x indicates the export status of a firm. Since tax exemptions apply to both output sold in the domestic market and to exports, the decisions to apply for tax exemptions and to export are interdependent. As in standard Melitz-type models,

[20] As in Melitz (2003), firms only differ in their export status and not their export share. To introduce additional variation in the export share, one can assume that Home is a SOE and introduce firm-specific fixed costs for each partner country in the ROW aggregate as in Blaum (2024).

there exist productivity cutoffs for firms selecting into exporting and tax exemptions, with more productive firms being more likely to engage in one or both activities.

3.3.4 Equilibrium

The equilibrium is given by a set of prices and an allocation such that consumers maximize their utility, firms maximize their profits, output and input markets clear, and trade is balanced.

3.4 Next Steps

This paper provides preliminary evidence on the distribution of tax exemptions across firms and industries using aggregate data. The next stage of the project has two main objectives: (i) to conduct a firm-level analysis of the effects of tax exemptions on exports and their interaction with carbon pricing policies, thereby complementing existing studies; and (ii) to quantify the general equilibrium consequences of tax exemptions using the model introduced in Section 3.3.

To address the first objective, I will merge information from the EU State Aid database with German administrative firm-level data, which provide detailed information on firms' energy use and trade activities. Based on exemption status and reported energy consumption, I will recover exact exemption values at the firm level. Because the EU State Aid database only covers exemptions above a reporting threshold, I plan to construct a more comprehensive list of exempted firms by collecting data from German federal agencies. In addition, I will merge information on firms' EU ETS participation and the free allocation of permits.

With this dataset, I can analyze the determinants of exemption status and treatment intensity across firms. A central question is whether exemptions predominantly benefit firms directly or indirectly regulated under the EU ETS, and whether firms with greater trade exposure are more likely to receive exemptions.

Since the primary justification for exemptions is to preserve international competitiveness, I will focus on their trade effects. This extends the work of Gerster and Lamp (2024) and Graevenitz and Rottner (2023), who study the effects of exemptions and energy prices on energy use. Using newly available product-level trade data with information on partner countries, I will examine how exemptions affect both the extensive margin of exports (entry and exit from foreign markets) and the intensive margin (export volumes, unit values, and export shares). I will also explore heterogeneity across products, in particular, whether effects are concentrated in energy-intensive goods.

Beyond direct effects, tax exemptions may generate general equilibrium spillovers by increasing misallocation and harming non-exempt firms. To capture these indirect effects, I will construct a measure of untreated firms' exposure based on their product mix. Firms with higher indirect exposure are more likely to lose market share both domestically and internationally.

The second objective is to evaluate the distortionary and general equilibrium effects of tax exemptions using the heterogeneous-firms model developed in Section 3.3. This framework allows me to quantify both firm-level responses and economy-wide reallocation in a unified setting. Specifically, I will compare outcomes under three scenarios: (a) the current policy, (b) an economy without tax exemptions, and (c) a policy that distributes the same aggregate exemption volume equally across firms. This comparison will highlight the policy's implications for welfare, emissions, and exports. In a further step, I will assess whether tax exemptions can mitigate carbon leakage under high carbon prices by simulating an increase in the domestic carbon price and comparing their effectiveness against alternative second-best policies, such as targeted export rebates.

3.5 Conclusion

This paper examines the effects of energy-related tax exemptions in German manufacturing. First, I document that exemption adoption varies substantially within and across sectors along both extensive and intensive margins. Second, exemptions also generate substantial heterogeneity in energy prices across firms and over time. Third, energy price heterogeneity is closely correlated with firm size, exports, and energy intensity.

To rationalize these findings, I develop a model of heterogeneous firms that face both energy and output distortions, introducing heterogeneity in energy prices that is correlated with firm size.

The next step is to calibrate the model to the German manufacturing sector and analyze two counterfactual scenarios. First, I will quantify the impact of abolishing energy tax exemptions on aggregate emissions, output, and exports, thereby assessing the environmental and welfare costs associated with these exemptions. Second, I will examine the effects of increasing the domestic carbon tax in a distorted economy, with a focus on international competitiveness and the potential role of export rebates in mitigating welfare losses and replacing untargeted tax exemptions.

While the paper currently focuses on energy tax exemptions, the proposed framework can quantify the economic costs of free allowances distributed to EU ETS firms deemed at high leakage risk. Follow-up research can also investigate the role of energy subsidies and tax exemptions in the adoption of clean R&D and capital investment, the entry of new firms, and the decline of clean industries.

Appendix to Chapter 3

C.1 Data Appendix

C.1.1 German Firm Data

To ensure data quality and consistency, firms with missing information on sales, energy use, energy costs, or material costs are excluded from the sample. Additionally, firms are dropped if they report annual energy consumption below 1,000 kWh or if any of the following variables are recorded as zero: energy costs, material costs, net production value, number of employees, or total wages. The analysis focuses on the period from 2011 to 2018, which aligns with two waves of the Cost Structure Survey data. Although applying these selection criteria reduces the sample to approximately 14,900 firms per year, this subsample continues to represent over 80% of total sales, energy consumption, and imports/exports within the original dataset. Despite the data-quality checks performed by the Statistical Office, inconsistencies and outliers remain. To address this, firm-year observations are flagged as potential outliers if any key variable deviates by more than 40% compared to the firm's values in adjacent years. Where data for both the preceding (t–1) and subsequent (t+1) years are available, missing or flagged values are imputed using the average of these two periods. This approach is applied consistently across all variables included in the analysis. To further enhance the analysis, firms are excluded if more than 50% of their observations are flagged as outliers, indicating persistently poor data quality.

Table C.1 reports descriptive statistics for the sampled firms in 2014. The average firm records sales of €110 million and employs 300 workers, with both variables displaying considerable dispersion. While energy prices are frequently highlighted as a determinant of international competitiveness, average energy expenditure is relatively modest at €2 million, accounting for 3% of total cost. Electricity and gas are the most used fuels, together representing 80% of consumption. 71% of firms export, with an average export share of 27% and 18 partner countries. Given this international orientation, policies affecting energy costs, including tax exemptions, may play a non-trivial role in firms' external competitiveness, particularly for energy-intensive producers.

Table C.1: Firm Summary Statistics

	Mean	**Median**	**SD**	**N**
Panel A: General variables				
Capital (million €)	52.38	6.29	639.34	14,900
Employees	303.25	91.00	2,248.83	14,900
Energy expenditure (million €)	2.13	0.25	14.57	14,900
Revenue per unit capital	339.06	2.21	20,456.21	14,553
Revenue per worker	230,146.78	151,848.03	509,960.88	14,900
Sales (million €)	110.65	14.69	1,364.70	14,900
Value added (million €)	43.68	7.29	429.25	14,900
Wages	36,147.35	35,027.05	14,346.09	14,900
Panel B: Energy and emissions				
CO_2 emissions (total, million t)	20,057.03	711.28	329,710.97	14,900
Emission intensity (kg CO_2/€)	0.12	0.05	0.44	14,900
Energy cost share	0.03	0.02	0.04	14,900
Energy consumption (million kWh)	66.92	1.80	1,146.56	14,900
Energy intensity (kWh/€)	0.41	0.13	1.89	14,900
Energy price (€/kWh)	0.14	0.13	0.10	14,900
Share of Coal	0.00	0.00	0.05	14,900
Share of Electricity	0.51	0.49	0.25	14,900
Share of Gas	0.32	0.29	0.29	14,900
Share of Oil	0.10	0.00	0.20	14,900
Panel C: Export activity				
Export share	0.27	0.19	0.27	14,871
Export status	0.71	1.00	0.45	14,900
Exports (million €)	48.87	2.30	765.82	14,895
Number of export partners	18.36	10.00	23.22	14,900

Notes: This table reports summary statistics for German firm-level data for the year 2014. All monetary values are in 2015 euros unless otherwise indicated. Export status is a binary indicator equal to one if the firm exports in a given year. Export share is measured as the ratio of export sales to total sales.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

C.1.2 Eurostat Energy Price Data

For the analysis, I use the Eurostat statistics *Gas prices components for non-household consumers - annual data (from 2007 onwards, code nrg_pc_203_c)* and *Electricity prices components for non-household consumers - annual data (from 2007 onwards, code nrg_pc_205_c)*. Both statistics cover the years 2017-2023 and report annual prices for each consumption band-country combination in all 27 EU member states, as well as an EU average price. The price can be disaggregated into three broad components: energy and supply costs, network costs, and taxes. The energy and supply costs relate to the costs of electricity generation and aggregation, as well as customer services and management costs. The network costs are region-specific and are charged via transmission and distribution tariffs based on the network operators' cost to maintain the electricity grid. Lastly, the tax component summarizes all the different taxes related to the purchase of electricity. This includes value-added taxes, capacity taxes, renewable taxes, environmental taxes, nuclear taxes, and all other taxes that occur.[21] Since both statistics start only in 2017, I complement those datasets with their more aggregate, bi-annual variants with information on the price paid by firms with and without taxes (*nrg_pc_203* and *nrg_pc_205*). With these data, I can study the long-run development of prices and taxes. When plotting the time trend across consumption bands, I select a representative consumption band for each of the small, medium, and large consumers. Similarly, when comparing Germany's energy prices to those of the other EU member states, I focus on the largest countries and the EU average.

C.1.3 EU State Aid Data

I classified state aid measures into five policy groups based on keywords in the measure titles.[22] In the next step, I excluded all policies that did not target the manufacturing sector. Additionally, I identified a misclassification where exemptions for cogeneration granted in 2018 had been recorded as being granted in 2019. I corrected these cases through contextual verification based on policy details and timing.

Two key plant-level descriptive variables, the industry classification and the tax exemption value, were initially provided in text or categorical formats. I recoded each plant's industry from its verbal description into official NACE Rev. 2 codes at the 2-digit level, using ChatGPT, trained on official industry activity descriptions. The tax exemption values were reported in seven brackets for around two-thirds of the observations. To convert these brackets into monetary values, I assigned the median value of each bracket to the respective plants, except for the open-ended highest bracket, where I allocated the lower bound value.

For the firm-level aggregation of state aid, I first standardized the unique firm identifiers across plants with identical names, as some included additional non-numeric characters. For each firm, I counted the number of plants and the total exemptions received. In cases where plants associated with the same firm were assigned different 2-digit industry codes or

[21]VAT is defined per Council Directive 2006/112/EC. Capacity taxes cover energy security, network, and regulatory costs. Renewable taxes support renewable energy, efficiency, and CHP. Environmental taxes include CO_2 emissions, air quality, and excise duties. Nuclear taxes relate to decommissioning and inspections. Other taxes include district heating, local charges, and infrastructure levies.

[22]These keywords are *EEG* for the EEG Surcharge Reduction, *Energiesteuergesetz* and *Energy Tax* for the energy tax, *Stromsteuergesetz* for the electricity tax, and *KWK*, *CHP*, *Kraft und Wärme*, and *cogeneration* for cogeneration. Even though firms can apply for exemptions to pay network charges, these are not officially recorded as state aid.

firm names, I retained the industry code and the name of the plant receiving the highest tax exemption. Lastly, I excluded all non-manufacturing firms from the final dataset.

In the following, I provide a list of the laws assigned to each aid group and the magnitude of exemptions:

EEG Surcharge Exemption (Erneuerbare-Energien-Gesetz)

- EEG 2014
- EEG 2017

The EEG surcharge for non-privileged consumers increased over the years, rising from 0.19 ct/kWh in 2000 to a peak of around 6.88 ct/kWh in 2017; afterward, it fluctuated slightly.

Energy Tax (Energiesteuergesetz)

- Tax relief for eligible installations according to § 3 Energy Tax Act
- Tax relief for other eligible installations according to § 3a Energy Tax Act
- Energy tax relief for own consumption according to § 47a Energy Tax Act
- General energy tax relief for manufacturing companies and companies in agriculture and forestry according to § 54 Energy Tax Act
- Energy tax relief for companies in special cases according to § 55 Energy Tax Act

Tax reductions under the Energy Tax vary by fuel type and exemption category, typically ranging from approximately 20% to 40% of the full tax rate, provided that the minimum tax liability of €250 is exceeded. These exemptions apply to fuels such as gas oils, natural gas, and liquefied gases. However, base tax rates for some fuels, like coal, are comparatively low.

Electricity Tax (Stromsteuergesetz)

- Tax exemption for electricity generated in installations with an electrical capacity of more than two megawatts from renewable energy sources and used exclusively for own consumption (§ 9 (1) no. 1 Electricity Tax Act)
- General electricity tax relief for manufacturing companies and companies in agriculture and forestry according to § 9b Electricity Tax Act
- Electricity tax relief for companies in special cases according to § 10 Electricity Tax Act (peak equalisation)

The electricity tax rate can be reduced from €20.5 per MWh to €15.37 per MWh under § 9b, provided that the minimum tax liability of €250 is exceeded. Additionally, a further reduction depends on the number of employees who contribute to a pension scheme. This additional reduction is granted on top of the § 9b reduction if the minimum tax liability of €1,000 is exceeded.

Cogeneration (Combined Heat and Power, Kraft-Wärme-Kopplungsgesetz)

- 2012 reform of support for cogeneration in Germany
- 2020 reform of support for cogeneration
- Full tax relief for the combined generation of power and heat according to § 53a (6) Energy Tax Act
- Partial tax relief for the combined generation of power and heat according to § 53a (1) or (4) Energy Tax Act
- Tax exemption for electricity generated in installations from renewable energy sources or highly efficient CHP installations, each with an electrical capacity of up to two megawatts, and used for own consumption or supplied to end-users in the immediate vicinity (§ 9 (1) no. 3 Electricity Tax Act)

Tax reductions for cogeneration provide full or partial exemptions depending on installation efficiency and fuel use. Full exemptions eliminate the energy tax on qualifying CHP fuels, while partial exemptions reduce tax liabilities proportionally. These benefits primarily apply to fuels such as gas oils and natural gas, with electricity from small renewable or highly efficient CHP units (up to 2 MW) also fully exempt from the electricity tax.

C.2 Additional Tables

Table C.2: Firm-level Determinants of the Energy Price

	Energy Price					
	(1)	(2)	(3)	(4)	(5)	(6)
Log Sales	-0.007***		-0.007***		-0.008***	
	(0.001)		(0.001)		(0.001)	
Log Energy Use		-0.018***		-0.017***		-0.018***
		(0.001)		(0.001)		(0.001)
Share Gas			0.011*	0.002	0.014**	0.003
			(0.006)	(0.005)	(0.007)	(0.005)
Share Oil			0.016***	-0.007	0.027***	-0.004
			(0.006)	(0.005)	(0.008)	(0.006)
Share Electricity			0.135***	0.107***	0.127***	0.096***
			(0.008)	(0.006)	(0.010)	(0.007)
Share Coal			0.001	0.033***	-0.030***	0.035***
			(0.010)	(0.009)	(0.009)	(0.009)
Dummy Dirty					-0.010	0.008
					(0.007)	(0.006)
State FE	✓	✓	✓	✓	✓	✓
Year × Ind FE	✓	✓	✓	✓		
Year FE					✓	✓
N	247,376	247,376	247,376	247,376	247,403	247,403
R^2	0.214	0.295	0.291	0.350	0.162	0.258

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. This table reports estimates from regressions of firm-level log energy prices on the log of sales. Additional controls include log energy use, and the shares of different fuel types in total energy consumption (gas, oil, electricity, and coal). *Dummy Dirty* indicates whether a firm operates in an EU ETS-covered sector. Energy use is measured in kWh and includes fuel and electricity consumption. The energy price is calculated by dividing total energy expenditure by total energy consumption in kilowatt-hours, including electricity. All specifications include state fixed effects and either year-by-industry fixed effects or year fixed effects, as indicated. Robust standard errors clustered at the industry level are reported in parentheses. All nominal variables are deflated to constant 2015 prices. The sample covers firms in the German manufacturing sector from 2011 to 2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table C.3: Firm-level Energy Intensity and Energy Price

	Log Energy Intensity						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log Energy Price	-4.467***	-4.571***	-2.901***	-4.021***	-2.444***	-5.232***	-2.769***
	(0.220)	(0.228)	(0.131)	(0.201)	(0.117)	(0.255)	(0.167)
Log Sales		-0.061***		-0.065***		-0.074***	
		(0.010)		(0.010)		(0.016)	
Log Energy Use			0.254***		0.251***		0.324***
			(0.011)		(0.010)		(0.013)
Share Gas				-0.388***	-0.231***	-0.403**	-0.199
				(0.075)	(0.057)	(0.165)	(0.121)
Share Oil				-0.577***	-0.022	-0.783***	0.007
				(0.081)	(0.061)	(0.165)	(0.119)
Share Electricity				-1.013***	-0.752***	-0.813***	-0.508***
				(0.103)	(0.066)	(0.188)	(0.128)
Share Coal				1.380***	0.724***	2.660***	1.279***
				(0.259)	(0.168)	(0.370)	(0.240)
Dummy Dirty						0.716***	0.335***
						(0.119)	(0.083)
State FE	✓	✓	✓	✓	✓	✓	✓
Year × Ind FE	✓	✓	✓	✓	✓		
Year FE						✓	✓
N	247,376	247,376	247,376	247,376	247,376	247,403	247,403
R^2	0.571	0.575	0.662	0.595	0.675	0.343	0.520

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. This table reports estimates from regressions of firm-level log energy intensity on the log of the firm-specific average energy price. Additional controls include log sales, log energy use, and the shares of different fuel types in total energy consumption (gas, oil, electricity, and coal). *Dummy Dirty* indicates whether a firm operates in an EU ETS-covered sector. Energy intensity is defined as the ratio of the firm's fuel and electricity consumption in kWh to its sales. Energy use is measured in kWh and includes fuel and electricity consumption. The energy price is calculated by dividing total energy expenditure by total energy consumption in kilowatt-hours, including electricity. All specifications include state fixed effects and either year-by-industry fixed effects or year fixed effects, as indicated. Robust standard errors clustered at the industry level are reported in parentheses. All nominal variables are deflated to constant 2015 prices. The sample covers firms in the German manufacturing sector from 2011 to 2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table C.4: Firm-level Exports and Energy Price

	Log Exports						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Energy Price	-3.365***	-0.851***	3.429***	-0.943***	2.615***	-1.415***	2.633***
	(0.273)	(0.099)	(0.199)	(0.113)	(0.189)	(0.228)	(0.249)
Log Sales		1.291***		1.289***		1.281***	
		(0.013)		(0.013)		(0.019)	
Log Energy Use			0.969***		0.970***		0.839***
			(0.018)		(0.016)		(0.021)
Share Gas				0.066	0.298***	0.022	0.324
				(0.050)	(0.086)	(0.098)	(0.200)
Share Oil				-0.019	-0.063	-0.054	-0.040
				(0.062)	(0.100)	(0.105)	(0.190)
Share Electricity				0.123**	1.060***	0.116	0.720***
				(0.059)	(0.112)	(0.112)	(0.227)
Share Coal				-0.569*	-1.584***	-0.909***	-2.441***
				(0.292)	(0.463)	(0.304)	(0.518)
Dummy Dirty						0.157	-0.312**
						(0.096)	(0.152)
State FE	✓	✓	✓	✓	✓	✓	✓
Year × Ind FE	✓	✓	✓	✓	✓		
Year FE						✓	✓
N	196,565	196,565	196,565	196,565	196,565	196,609	196,609
R^2	0.239	0.739	0.597	0.739	0.606	0.672	0.450

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. This table reports estimates from regressions of firm-level log exports on the log of the firm-specific average energy price. Additional controls include log sales, log energy use, and the shares of different fuel types in total energy consumption (gas, oil, electricity, and coal). *Dummy Dirty* indicates whether a firm operates in an EU ETS-covered sector. Energy use is measured in kWh and includes fuel and electricity consumption. The energy price is calculated by dividing total energy expenditure by total energy consumption in kilowatt-hours, including electricity. All specifications include state fixed effects and either year-by-industry fixed effects or year fixed effects, as indicated. Robust standard errors clustered at the industry level are reported in parentheses. All nominal variables are deflated to constant 2015 prices. The sample covers firms in the German manufacturing sector from 2011 to 2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

Table C.5: Firm-level Export Share and Energy Price

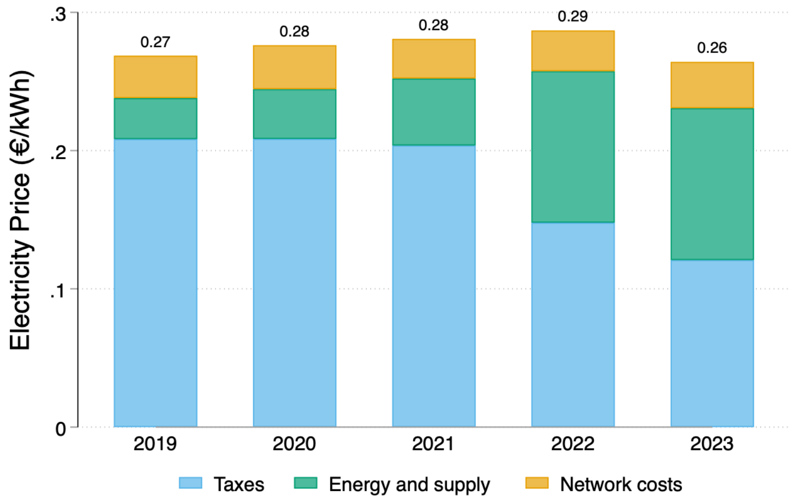
	Export Share						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Energy Price	-0.217***	-0.119***	0.048***	-0.127***	0.016	-0.241***	-0.125***
	(0.020)	(0.015)	(0.015)	(0.017)	(0.016)	(0.031)	(0.033)
Log Sales		0.058***		0.058***		0.063***	
		(0.003)		(0.003)		(0.003)	
Log Energy Use			0.043***		0.044***		0.034***
			(0.002)		(0.002)		(0.003)
Share Gas				0.003	0.017*	-0.013	-0.005
				(0.008)	(0.010)	(0.023)	(0.028)
Share Oil				-0.007	-0.004	-0.030	-0.047*
				(0.010)	(0.011)	(0.022)	(0.028)
Share Electricity				0.007	0.051***	0.005	0.030
				(0.011)	(0.013)	(0.021)	(0.025)
Share Coal				-0.129**	-0.171***	-0.226***	-0.274***
				(0.052)	(0.058)	(0.059)	(0.065)
Dummy Dirty						0.030	0.018
						(0.023)	(0.025)
State FE	✓	✓	✓	✓	✓	✓	✓
Year $\times$ Ind FE	✓	✓	✓	✓	✓		
Year FE						✓	✓
N	245,923	245,923	245,923	245,923	245,923	245,951	245,951
R^2	0.320	0.402	0.378	0.402	0.380	0.194	0.129

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. This table reports estimates from regressions of firm-level export share on the log of the firm-specific average energy price. Additional controls include log sales, log energy use, and the shares of different fuel types in total energy consumption (gas, oil, electricity, and coal). *Dummy Dirty* indicates whether a firm operates in an EU ETS-covered sector. Energy use is measured in kWh and includes fuel and electricity consumption. The export share is defined as exports divided by sales. The energy price is calculated by dividing total energy expenditure by total energy consumption in kilowatt-hours, including electricity. All specifications include state fixed effects and either year-by-industry fixed effects or year fixed effects, as indicated. Robust standard errors clustered at the industry level are reported in parentheses. All nominal variables are deflated to constant 2015 prices. The sample covers firms in the German manufacturing sector from 2011 to 2018.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

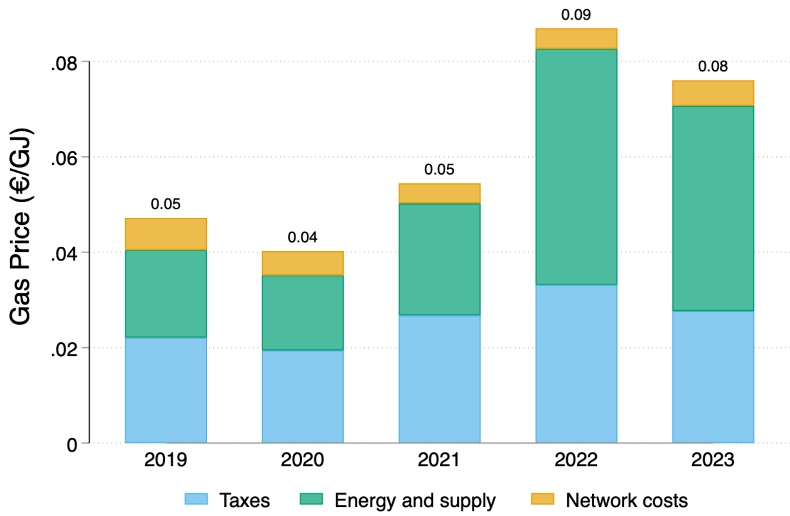
C.3 Additional Figures

C.3.1 Energy Prices in Germany for Industrial Consumers

Figure C.1: Electricity and Gas Price Components in Germany



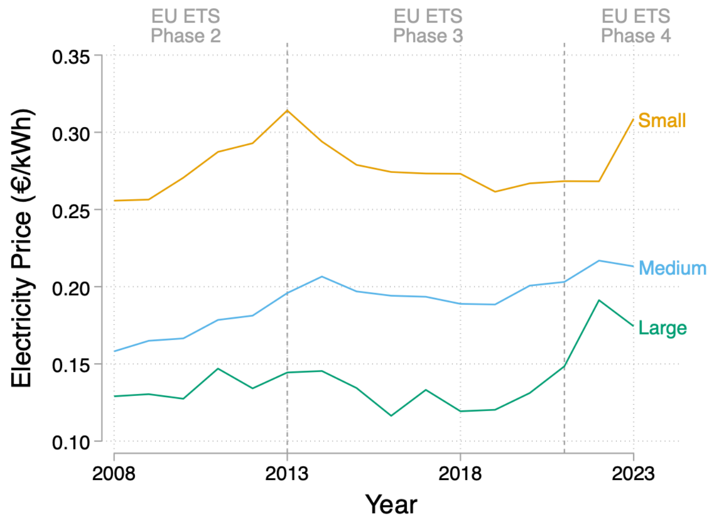
(a) Electricity Price



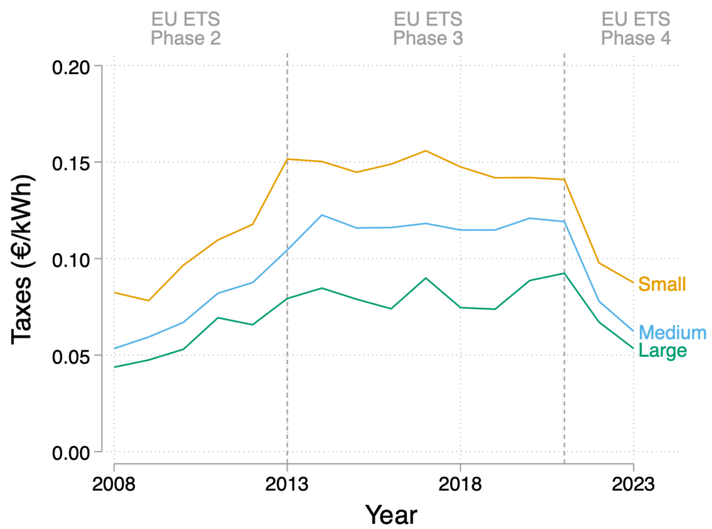
(b) Gas Price

Notes: This figure shows the time series variation in energy price components for industrial consumers in Germany, averaged across all consumption bands, from 2019 to 2023. The price components include taxes, energy costs, and network costs. Panel (a) shows the electricity price components in 2015 €/kWh. Panel (b) shows the gas price components in 2015 €/GJ.
Source: Eurostat's electricity and gas prices components statistics.

Figure C.2: Trends in Electricity Prices by Consumption Band



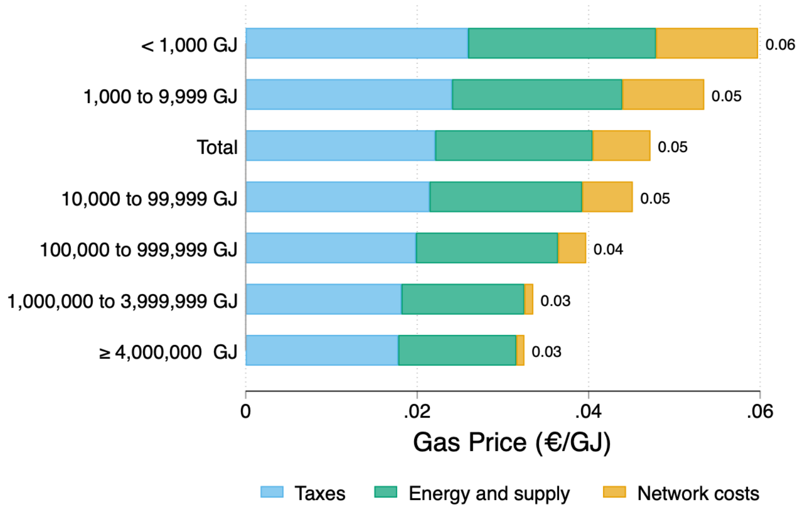
(a) Total Price



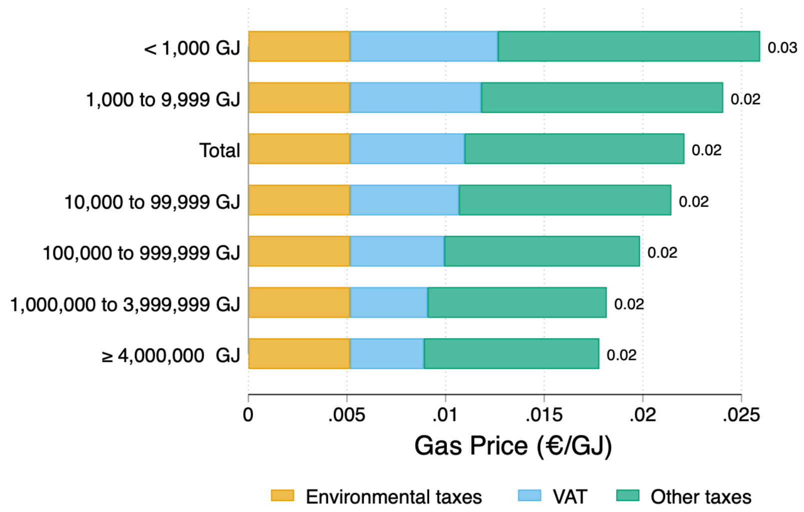
(b) Taxes

Notes: This figure shows the time series variation in electricity prices in 2015 €/kWh for industrial consumers across three different consumption bands in Germany, from 2007 to 2023. Panel (a) shows the total electricity price, Panel (b) focuses on the tax components. The bands are defined as follows: *<20 MWh* for small consumers, *500 to 1,999 MWh* for medium-sized consumers, and *70,000 to 149,999 MWh* for large consumers.
Source: Eurostat's electricity prices statistics.

Figure C.3: Gas Price and Tax Components by Consumption Band



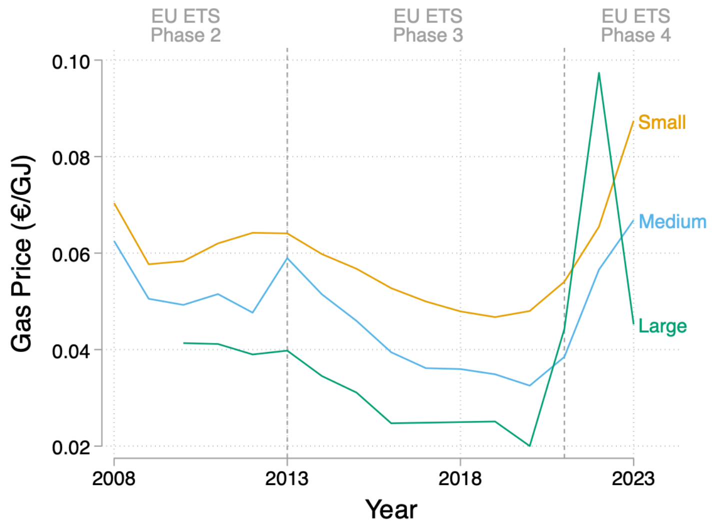
(a) Gas Price Components



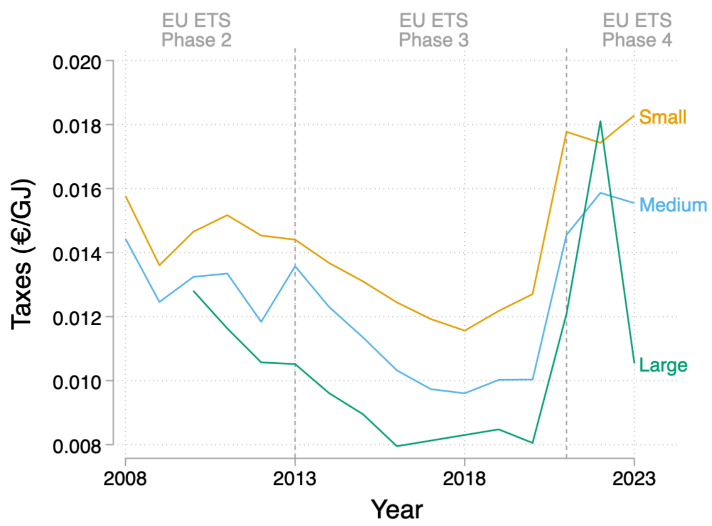
(b) Tax Components

Notes: This figure shows the composition of gas prices for industrial consumers in Germany in 2019 across various consumption bands, measured in €/GJ. Panel (a) disaggregates prices into three components: energy and supply costs, network costs, and taxes. Panel (b) further breaks down the tax component into environmental taxes, value-added tax (VAT), and other taxes. Industrial consumers are divided into six consumption bands, ranging from less than 1,000 GJ to 4,000,000 GJ or more. A total consumption category is also included, representing the average price for all industrial consumers.
Source: Eurostat's gas price components statistics.

Figure C.4: Trends in Gas Prices by Consumption Band



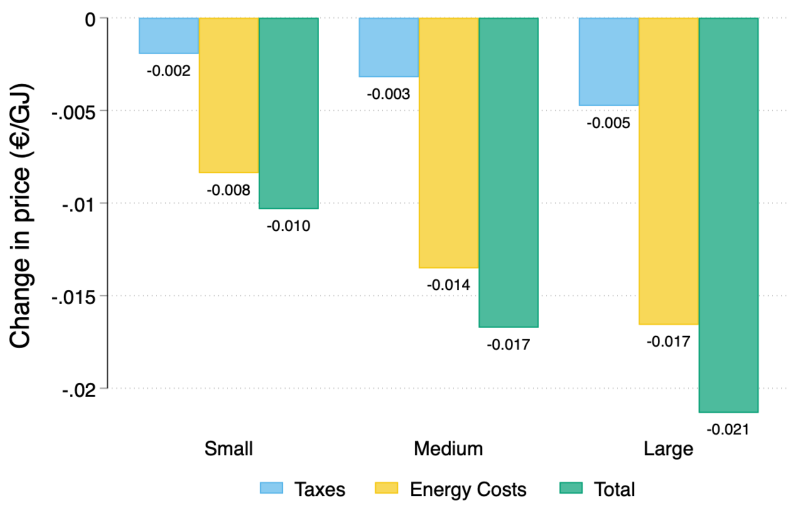
(a) Total Price



(b) Taxes

Notes: This figure shows the time series variation in gas prices (€/GJ) for industrial consumers across three different consumption bands in Germany, from 2008 to 2023. Panel (a) shows the total gas price, Panel (b) focuses on the tax components. The bands are defined as follows: *<1,000 GJ* for small consumers, *10,000 to 99,999 GJ* for medium-sized consumers, and > *4,000,000 GJ* for large consumers.
Source: Eurostat's gas prices statistics.

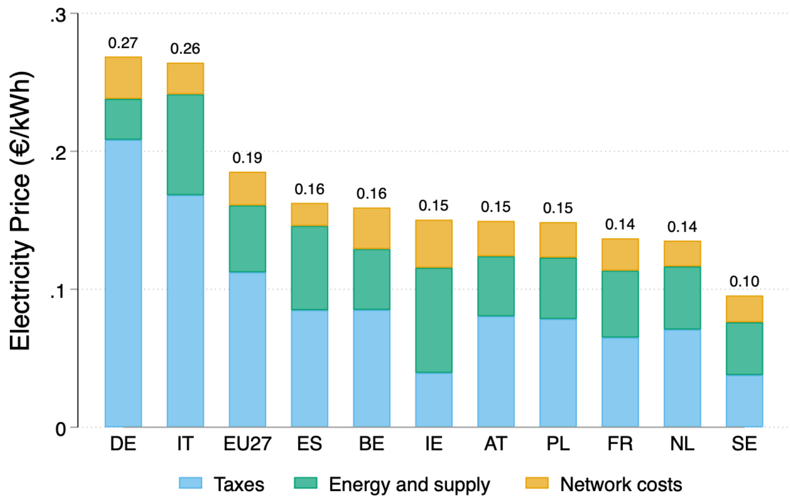
Figure C.5: Decomposition of Gas Price Changes



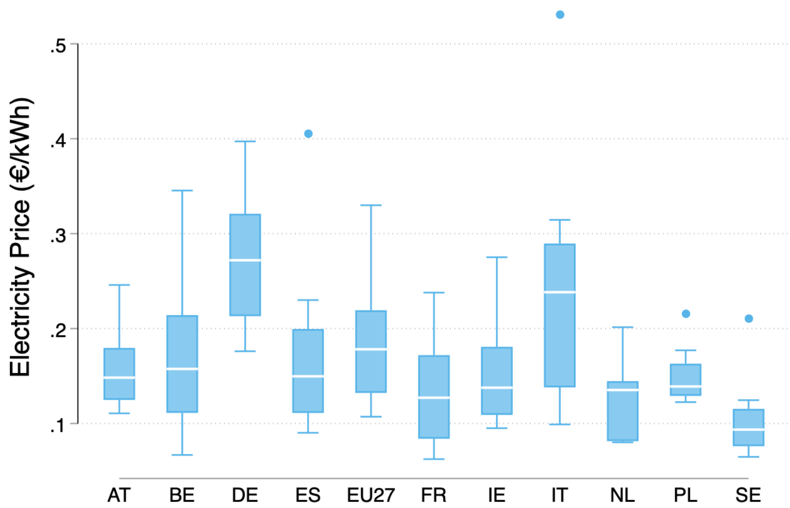
Notes: This figure shows a decomposition of the change in gas prices for industrial consumers in Germany between 2007 and 2020, expressed in constant 2015 €/GJ, across different consumption bands. Prices are disaggregated into two components: Energy Costs and Taxes. The sum of these components equals the total aggregate price change, which is also reported. Consumption bands are defined as follows: *<1,000 GJ* for small consumers, *10,000 to 99,999 GJ* for medium-sized consumers, and *> 4,000,000 GJ* for large consumers.
Source: Eurostat's gas price statistics.

C.3.2 External Validity of Energy Price Results

Figure C.6: Industrial Electricity Prices in the EU



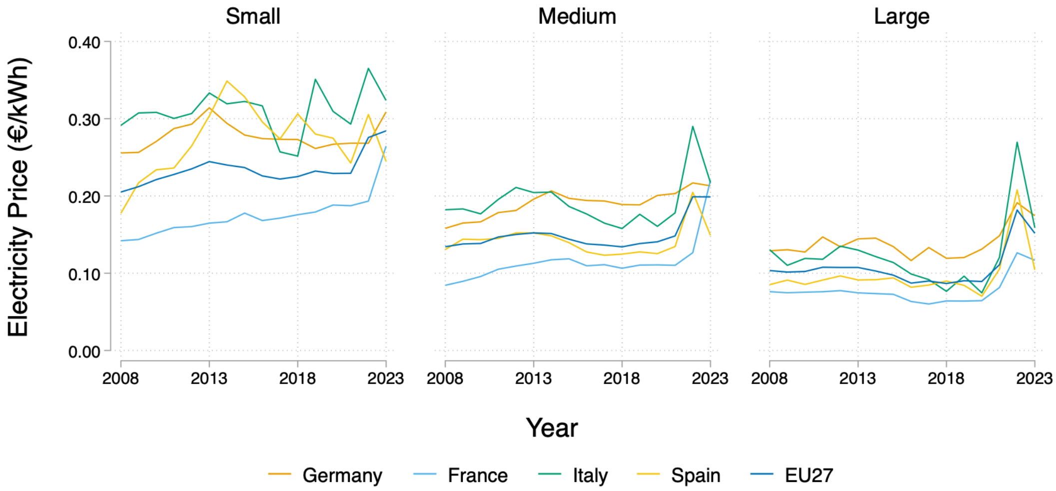
(a) Electricity Price Components by Country



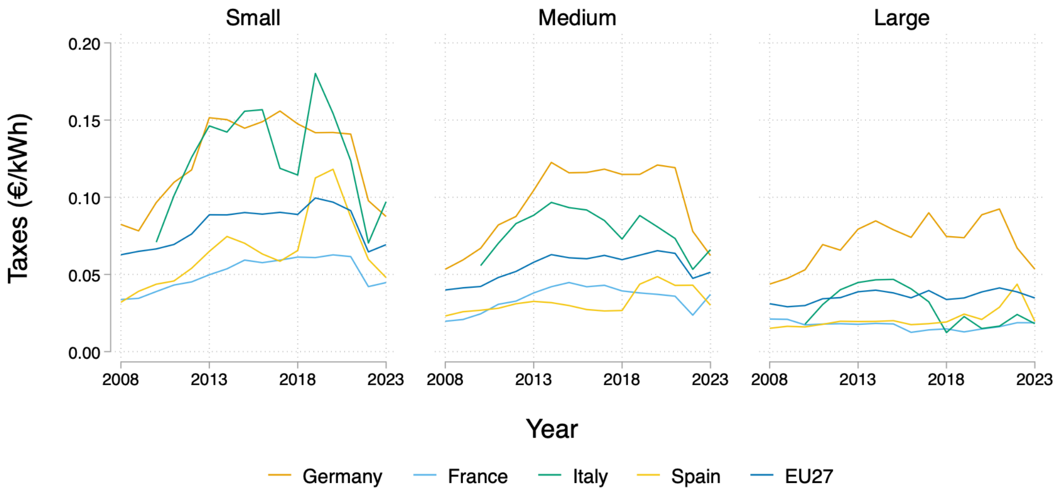
(b) Electricity Price Distributions by Country

Notes: Panel (a) shows the composition of electricity prices for industrial consumers in the largest EU countries and the EU in 2019, expressed in 2015 €/kWh. Prices are disaggregated into three components: Energy and Supply, Network Costs, and Taxes. Panel (b) shows the distribution of total electricity prices across the same set of countries in 2019, in 2015 €/kWh. Prices are reported for the total consumption category, representing the average price for all industrial consumers in a country.
Source: Eurostat, electricity price components statistics.

Figure C.7: Trends in Electricity Prices and Taxes in the EU



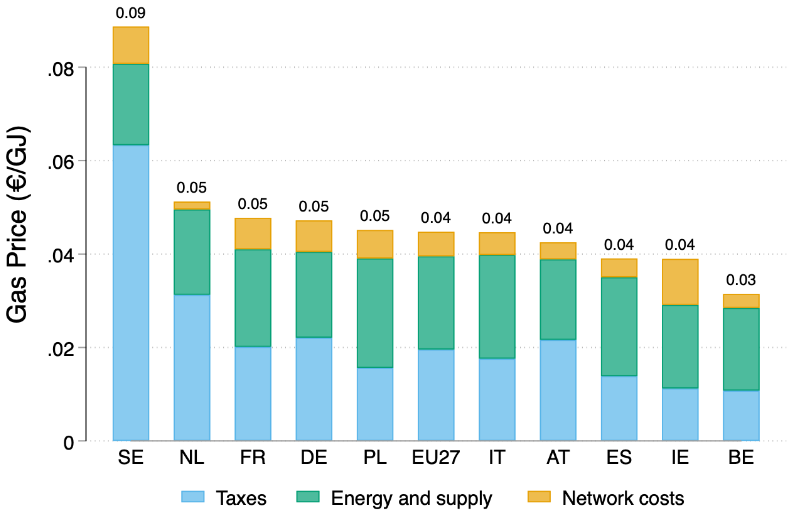
(a) Trends in Electricity Prices by Country



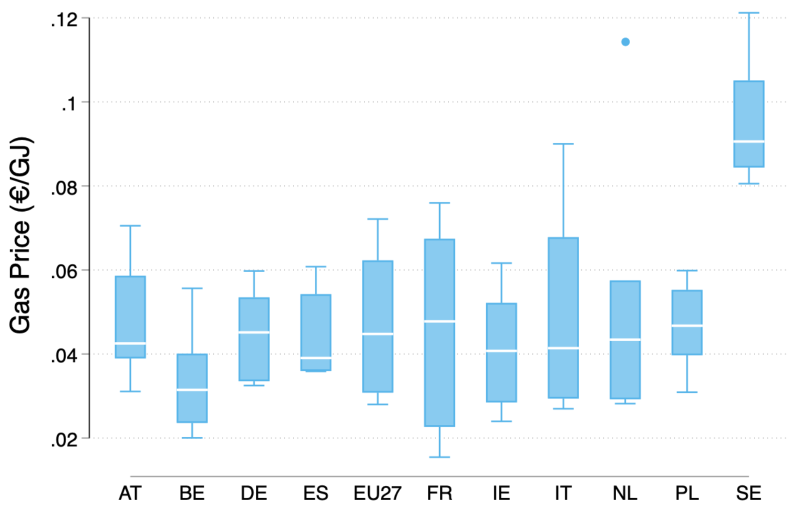
(b) Trends in Electricity Taxes by Country

Notes: Panel (a) shows the time series of electricity prices, while Panel (b) shows electricity taxes (both in 2015 €/kWh) for industrial consumers in the largest EU countries and the EU, from 2008 to 2023. The bands are defined as follows: *<20 MWh* for small consumers, *500 to 1,999 MWh* for medium-sized consumers, and *70,000 to 149,999 MWh* for large consumers.
Source: Eurostat's electricity prices statistics.

Figure C.8: Industrial Gas Prices in the EU



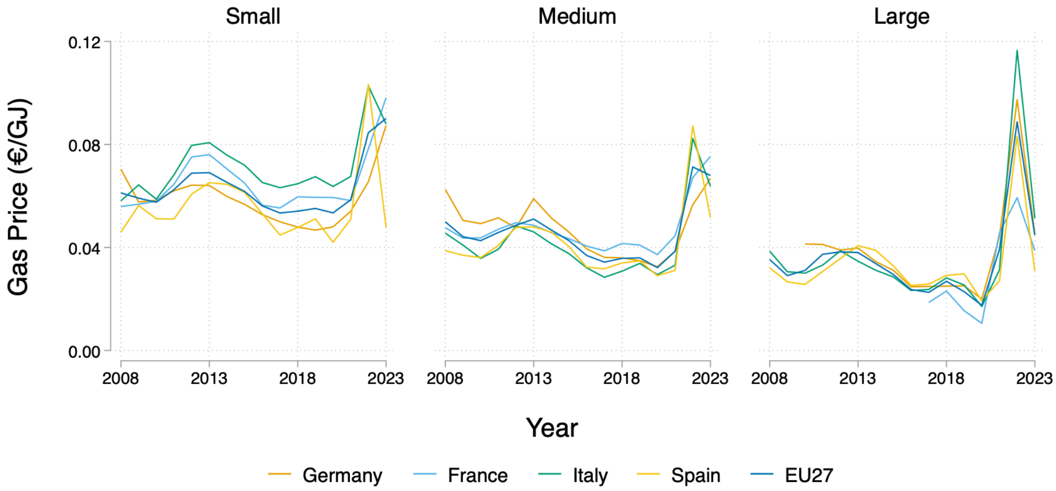
(a) Gas Price Components by Country



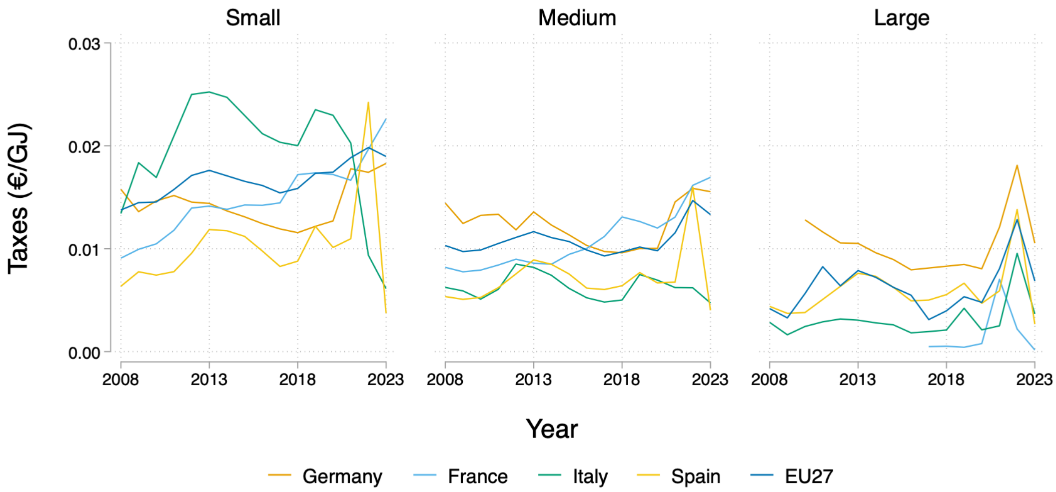
(b) Gas Price Distributions by Country

Notes: Panel (a) shows the composition of gas prices for industrial consumers in the largest EU countries and the EU in 2019, expressed in 2015 €/GJ. Prices are disaggregated into three components: Energy and Supply, Network Costs, and Taxes. Panel (b) shows the distribution of total gas prices across the same set of countries in 2019, in 2015 €/GJ. Prices are reported for the total consumption category, representing the average price for all industrial consumers in a country.
Source: Eurostat's gas price components statistics.

Figure C.9: Trends in Gas Prices and Taxes in the EU



(a) Trends in Gas Prices by Country

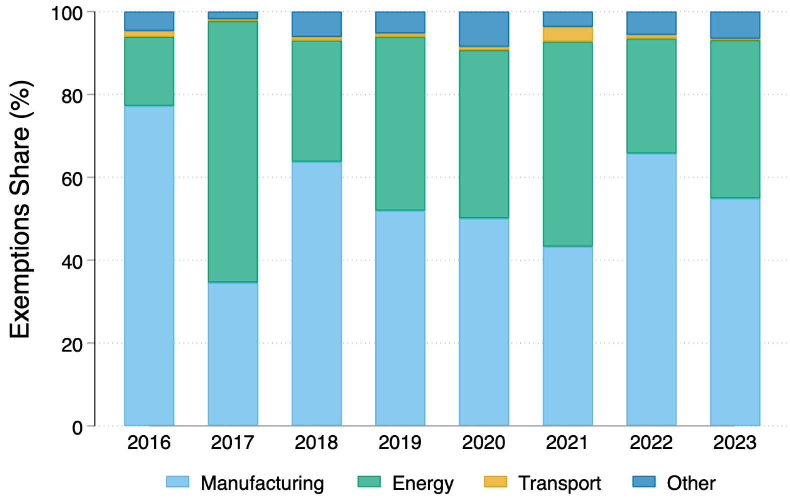


(b) Trends in Gas Taxes by Country

Notes: Panel (a) shows the time series of gas prices, and Panel (b) shows gas taxes (both in 2015 €/GJ) for industrial consumers in the largest EU countries and the EU from 2008 to 2023. The bands are defined as follows: *<1,000 GJ* for small consumers, *10,000 to 99,999 GJ* for medium-sized consumers, and > *4,000,000 GJ* for large consumers.
Source: Eurostat's gas price statistics.

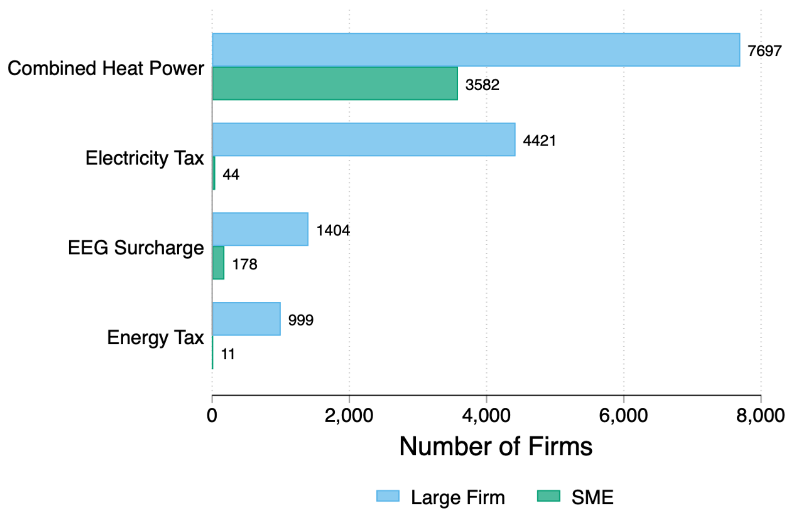
C.3.3 State Aid in Germany

Figure C.10: Distribution of Energy Exemptions by Sector



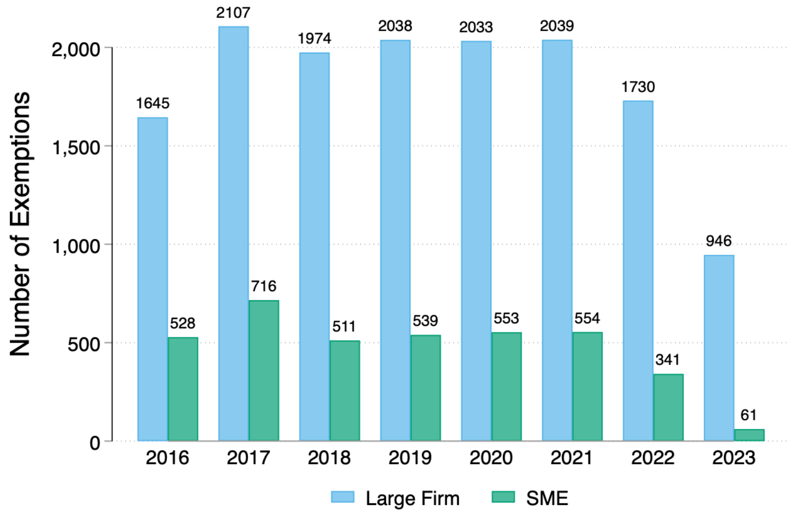
Notes: This figure shows the share of total energy-related exemptions received by firms in each sector in Germany between 2016 and 2023. The share is calculated by aggregating the exemptions granted to firms within a sector and dividing by the total amount of exemptions granted across all sectors. Sectors are classified by NACE codes: Manufacturing (10–33), Energy (35, 36, 39), Services (45–99), and all remaining industries as Other.
Source: EU State Aid Transparency Database.

Figure C.11: Type of Energy Tax Exemptions in Germany by Firm Size

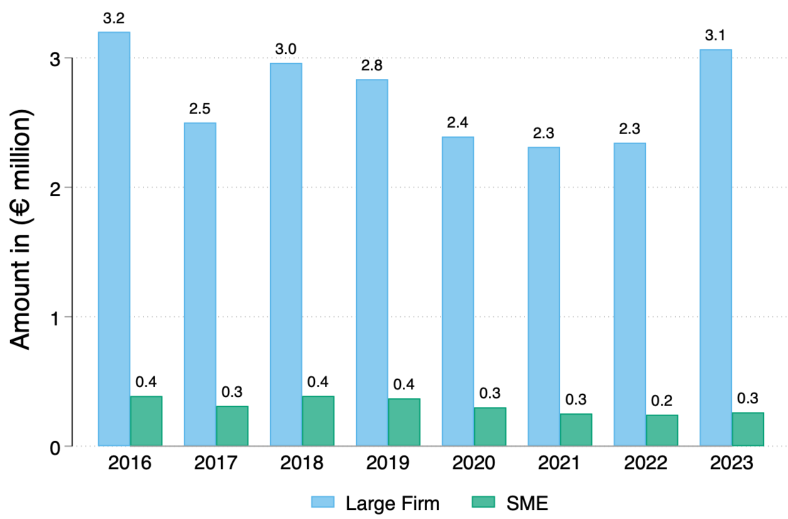


Notes: This figure shows the annual number of exemptions granted in Germany by firm size and exemption type in 2019. Exemptions are classified into four categories: EEG surcharge, energy tax, CHP, and electricity tax. Firms employing fewer than 250 individuals are classified as small and medium-sized enterprises (SMEs), while those with 250 or more employees are categorized as large firms.
Source: EU State Aid Transparency Database.

Figure C.12: Energy Tax Exemptions in Germany by Firm Size



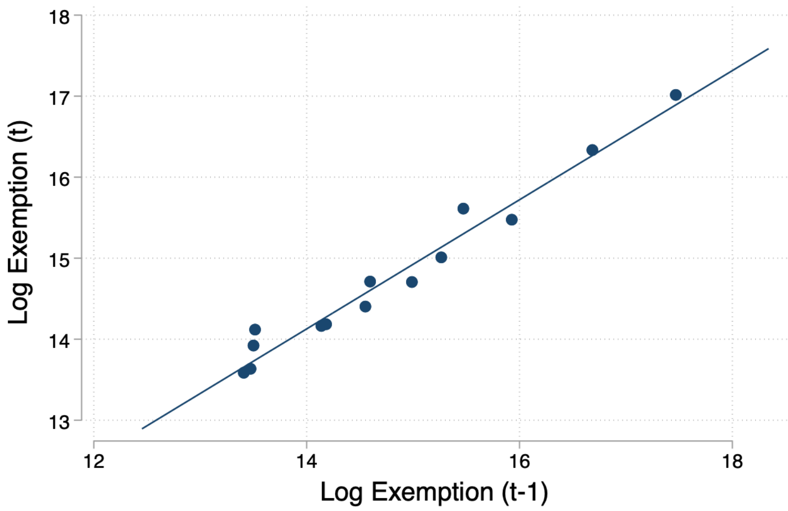
(a) Number of Exemptions



(b) Expenditure on Exemptions

Notes: This figure shows the distribution of energy-related tax exemptions in Germany by firm size from 2016 to 2023. Panel (a) shows the annual number of exemptions granted, while Panel (b) depicts the corresponding expenditure in million €(2015 prices). Firms employing fewer than 250 individuals are classified as small and medium-sized enterprises (SMEs), while those with 250 or more employees are categorized as large firms.
Source: EU State Aid Transparency Database.

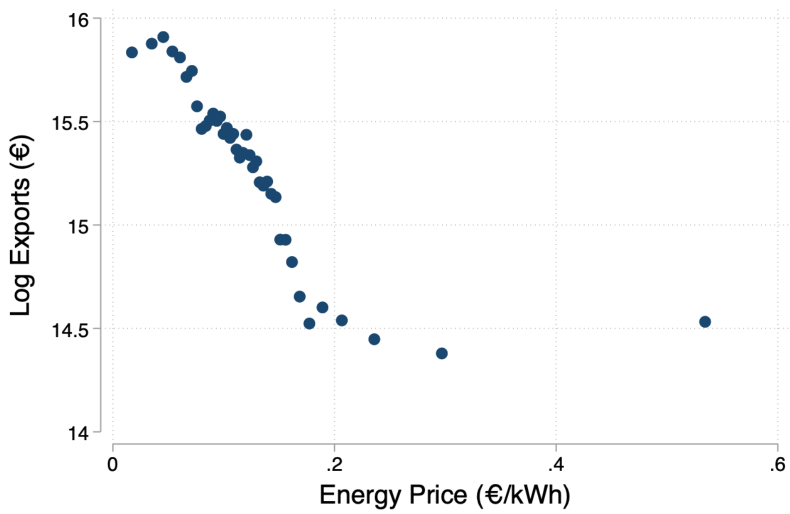
Figure C.13: Persistence of Tax Exemptions



Notes: This figure displays persistence of the intensive margin of tax exemptions between 2016 and 2021. The value of exemptions received is expressed in 2015 €. Exemptions refer to relief from the EEG surcharge and electricity tax.
Source: EU State Aid Transparency Database.

C.3.4 Firm Characteristics and Energy Prices

Figure C.14: Energy Prices and Exports in German Manufacturing



Notes: This figure shows a binscatter plot examining the relationship between firm-level energy prices and exports, using German administrative data for the manufacturing sector from 2011 to 2018. The figure plots log(energy price) as the dependent variable against log(exports), controlling for four-digit industry and year fixed effects. Observations are grouped into equally sized bins based on the independent variable, and the means of both variables are calculated within each bin. The dependent variable is residualized to account for fixed effects. All nominal values are deflated to constant 2015 prices.
Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Federal States of Germany, AFiD-Modul Energieverwendung 1998–2019, AFiD-Panel Industriebetriebe 1998–2019, AFiD-Panel Industrieunternehmen 1998–2019, project-specific preparations, own calculations.

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Declaration

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbstständig angefertigt und die benutzten Hilfsmittel vollständig und deutlich angegeben habe.

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