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DISCUSSION PAPER

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# Is Germany Becoming the European Pollution Haven?

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# Is Germany becoming the European pollution haven?

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**Abstract**

Relative prices determine competitiveness of different locations. In this paper, we focus on the role of regulatory differences between Germany and other EU countries which affect the shadow price of carbon emissions. We calibrate a Melitz-type model, extended by firms' emissions and abatement decisions using data on aggregate output, trade and emissions. The parameter estimates are estimated from the German Manufacturing Census. The quantitative model allows us to recover a measure of how regulatory stringency evolved in the EU and Germany in terms of an implicit carbon price paid on emissions. This price reflects energy and carbon prices in addition to command-and-control measures and decreased from 2005 to 2019 in most sectors – both in Germany and other EU countries. The trend is more pronounced in Germany than in the rest of the EU. In counterfactual analyses, we show that this intra-EU difference has substantially increased German industrial emissions. Had the EU experienced the same decrease in implicit carbon prices as Germany, German emissions would have been substantially lower. Germany has increasingly become a pollution haven.

**Keywords:** Carbon emissions, Climate Policy, Melitz model, Manufacturing

**JEL-Classification:** F18, H23, L60, Q56

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# 1 Introduction

Drastic reductions of greenhouse gas emissions are necessary to limit global warming to below two degrees celsius. This concerns also the industrial sector, which in 2010 accounted for more than 30 % of greenhouse gas emissions globally, exceeding the respective shares of transportation and buildings (IPCC, 2014). Climate policies to reduce industrial carbon emissions remain a largely national affair with substantial heterogeneity across countries. However, even where such policies are implemented and ambitions are high, a reduction in emissions has not necessarily materialized: In Germany, carbon emissions from manufacturing have increased between 2003 and 2017 by about 32 million tonnes; carbon intensity as measured by emissions per Euro of gross output has declined only slightly (Rottner and von Graevenitz, 2021). This is in spite of regulation through the EU ETS and rising electricity prices due to taxes and levies such as electricity network charges and the renewable energy surcharge. What is more, the increase in carbon emissions occurs over a period in which existing research has mostly found these individual policy measures to be effective in ex-post causal effect analyses (see e.g. Gerster and Lamp, 2022 and von Graevenitz and Rottner, 2022 on the effects of electricity prices, and Lehr *et al.*, 2020 on the effect of the EU ETS). If climate policies are effective at reducing emissions all else equal, why have emissions increased nevertheless?

In this paper, we shed light on one factor which cannot be made explicit in classic reduced-form ex-post programme evaluation: Specifically, we analyse the roles played by climate regulation in other countries and international trade. For that purpose, we use the quantitative model linking environment and trade developed by Shapiro and Walker (2018). We apply their model to a three country world (Germany, rest of EU, rest of the world) to account for the embeddedness of Germany within the EU. Feeding the formal model relations with data on trade (from Eurostat), production (from INDSTAT), and emissions (from the IEA), as well as values for central model parameters (estimated from the German Manufacturing Census) allows us to retrieve a measure of the historic development of implicit carbon prices faced by firms in the EU and Germany. Essentially, we back out the values carbon prices must have taken, given the model structure we impose, in order to rationalise the outcomes in terms of trade, production and emissions that actually occurred. We contrast the development of implicit carbon prices in the EU and Germany, and relate them to changes in energy and carbon prices using regression analysis. While emission prices follow a similar trend in both world regions, German regulation stringency declines more than in the rest of the EU. In a decomposition analysis, we show that the development of implicit carbon prices in general, and also the difference between German and EU prices specifically, are influential in shaping the development of carbon emissions in German industry. Germany seems to have developed in the direction of a ”pollution haven” for carbon. In a counterfactual analysis, we demonstrate that the carbon emissions of German manufacturing would have been substantially lower, had both world regions experienced identical developments in their implicit carbon prices. The main driver is the German metal sector, which would have grown substantially less in the counterfactual.

Debates about the impact of differences in terms of regulatory stringency are high on the policy agenda. Given the common European climate policy in form of the EU ETS, these discussions have mostly focused on differences between EU and non-EU countries. Our analysis suggests that intra-European differences in implicit carbon prices are important. In line with basic findings from the trade and gravity literature, our results indicate that trade linkages and the danger of production shifts are much stronger within than outside of the EU.[1] The decomposition exercise we implement to separate the importance of different model drivers attributes a much weaker effect to changes in the competitiveness (including climate regulation) of countries in the rest of the world for the German emissions development, than to changes in EU competitiveness and EU climate regulation. In consequence, our results imply we should not only be discussing the CBAM, but also examine intra-European differences in implicit carbon prices. Unilateral climate and energy policies within the EU can undermine the allocative efficiency of the ETS.

With this paper, we add to to two strands of literature. First, we complement research on econometric ex-post evaluation of single climate policies (among others, Colmer *et al.* 2023 or Martin *et al.* 2016). Our paper contributes to this literature by offering a new perspective that takes changes in other countries, feedback effects between sectors and macroeconomic adjustments into account. Second, we add to the literature using general equilibrium models in the study of climate policies (– see Böhringer *et al.* 2012 for an overview of different computable general equilibrium, CGE, models). We follow the bur-

[1]See, e.g., Bergstrand *et al.* (2015); Baier and Bergstrand (2009, 2007); Disdier and Head (2008) or Yotov (2012) on the elasticity of distance and on the effects of trade agreements in gravity equations.

geoning strand of literature using a structural gravity setup borrowed from international trade (Caron and Fally, 2022; Egger and Nigai, 2015; Shapiro, 2016). While these models sacrifice some detail in terms of structure as compared to typical CGE models, they offer higher tractability. Many of these studies have quantified models for ex-ante simulation (e.g., of carbon border adjustments, such as in Farrokhi and Lashkaripour 2022; Larch and Wanner 2017; Sogalla 2023). In contrast, we apply the framework to understand past emissions developments, thereby bridging the gap between reduced form ex-post and model-based ex-ante evaluation.

The remainder of this paper is structured as follows: Section 2 presents the amended Melitz-style model as set up by Shapiro and Walker (2018) and discusses relevant model assumptions. Section 3 presents the data used for the quantification of the model and estimates the relevant model parameters. In Section 4, we use the model to back out the historical development of the stringency of climate regulation in Germany and the EU. We also run regressions to explain these developments by energy and permit prices under the EU ETS. Section 5 uses the model and the parameter estimates for counterfactual analysis. Specifically, we first decompose the German emissions development to disentangle the roles of German and EU implicit carbon prices, as well as competitiveness changes in the rest of the world. Second, we show how German emissions would have developed had EU climate regulation developed identically to the German one. Finally, Section 6 concludes.

# 2 The model

To explain the development of carbon emissions in German manufacturing, we apply the quantitative model set up by Shapiro and Walker (2018). In this section, we briefly describe the model and discuss the main model assumptions.[2]

The model is a static Melitz-style model of monopolistic competition with heterogeneous firms (Melitz, 2003). Production is associated with emissions and firms can sacrifice output to abate. Differences in productivity lead firms to differ in terms of their abatement investments and the resulting carbon emissions. The model features endogenous firm entry, production and export decisions. Labour, the only production factor, is

[2] For details, we refer the reader to the original paper by Shapiro and Walker (2018).

inelastically supplied. For ease of exposition we will consider a world of two countries, the *origin* $o$, or *domestic* country, and the *destination* or *foreign* country $d$ in the following. The model extends to any number of countries. In our application we have a three country world (Germany, the rest of the EU, and the rest of the world).

The representative consumer in each country maximises utility. Consumers allocate their income across sectors with expenditure shares $\beta_{i,s}$ that sum up to 1 across all sectors. Within sectors, they allocate their budget on varieties $\omega$ produced in country $i \in \{o, d\}$ and consume quantities $q_{oi,s}$. Each variety is only produced in one country. Utility is of a constant elasticity of substitution (CES) form across varieties within a sector $s$, but Cobb-Douglas across sectors. Formally, the utility function (here, of country $o$) takes the following form:

$$U_o = \prod_s \left( \left[ \sum_i \int_{\omega \epsilon \Omega_{i,s}} q_{oi,s}(\omega)^{\frac{\sigma_s - 1}{\sigma_s}} d\omega \right]^{\frac{\sigma_s}{\sigma_s - 1}} \right)^{\beta_{o,s}} \tag{1}$$

where $\sigma_s$ represents the sector-specific elasticity of substitution across varieties. The functional form leads to consumers experiencing an increasing utility in the total measure of varieties (the "love for variety").

Firms that differ in their productivity $\varphi$ engage in monopolistic competition. Conditional on entering the market, firms in origin $o$ choose prices $p_{oi,s}$ charged in country $i$ to maximise profits

$$\pi_{oi,s}(\varphi) = p_{oi,s}(\varphi) q_{oi,s}(\varphi) - w_o l_{oi,s}(\varphi) \tau_{oi,s} - t_{o,s} z_{oi,s}(\varphi) \tau_{oi,s} - w_i f_{oi,s} \tag{2}$$

There is only one production factor required, labour $l_{ois}$ which is employed at the (not sector-specific) domestic wage rate $w_o$.[3] Selling in market $i$ involves both variable iceberg trade costs $\tau_{oi,s}$, such that $\tau_{oi,s} \geq 1$ units must be shipped for one unit to arrive, and fixed costs $f_{oi,s}$. Both trade cost parameters are equal to 1 for domestic sales. Emissions $z_{oi,s}$ generated as a by-product for selling to country $i$ are taxed at sector-specific rates $t_{o,s}$.[4] This price on emissions does not only reflect carbon taxes that are directly charged on emissions, but also comprises energy prices. This is because emissions (from fuel

[3]Note that while the model set-up features labour as the sole production factor, it can be thought of as a composite of different production factors.

[4]Tax revenues are lost to rent-seeking. This is a simplifying assumption, but not entirely implausible: As of September 2023, 29.1% of entries in the German Lobby Register concern the topic of energy (see https://www.lobbyregister.bundestag.de/startseite?lang=de). According to the EU transparency

combustion) are completely driven by energy consumption, as there is no end-of-pipe technology for carbon emissions available. Implicit prices on emissions are in fact prices on energy consumption plus any additional tax or other type of regulation imposing costs (shadow price of carbon) related to the associated emissions. Profit maximisation leads to prices being set as a constant proportional markup over marginal cost. Equations 9 and 10 in the Appendix show prices and marginal cost.

Firms can only enter the market if they pay additional sunk entry-costs $f^e_{o,s}$. Only after doing so, they observe their draw $\varphi$ from a Pareto productivity distribution. We index firms according to their productivity draw. The Pareto distribution is characterized by a location parameter $b_{o,s}$ describing $o$'s productivity, and a shape parameter $\theta_s$ describing the productivity dispersion in a sector. Firms can still decide not to produce after having observed their productivity draw. Only firms with a draw above an endogenous productivity threshold will find it profitable to produce. As exporting comes with additional cost ($f_{oi,s}$ and $\tau_{oi,s}$) only a subset of these firms are productive enough to profit from exporting to foreign markets. Details on the Pareto distribution and the cutoff productivity are relegated to the Appendix.

Firms produce output with a Cobb-Douglas technology using emissions and labour as input factors:

$$q_{oi,s} = (z_{oi,s})^{\alpha_s}(\varphi l_{oi,s})^{(1-\alpha_s)} \tag{3}$$

The pollution elasticity $\alpha_s$ represents the Cobb-Douglas share of emissions. This Cobb-Douglas form is crucial for the tractability of the model. Note that this production technology also can be derived from the assumption of a Copeland and Taylor (2003) emission technology, assuming profit maximisation and optimal abatement. The corresponding emission technology allows for the interpretation of emissions as both an additional production factor, which is priced, or as a second output on which firms are taxed. Details are shown in Appendix 7.

Let us highlight some important implications of this model set-up:

register, ArcelorMittal, the world's second biggest steel producer, spends approximately 1.25-1.5 million Euros each year on activities covered by the register. For the Dow Europe GmbH (chemicals and plastics), this sum amounts to 3-3.5 million Euros – and is even higher in the case of ExxonMobil Petroleum & Chemical (3.5-4 million Euros). The Thyssenkrupp Steel AG reports lobby spendings of 700,000-800,000 Euros. Winkler (2022) finds that in the EU, lobbying for higher numbers of free emission allowances was valuable and increased free allocation under the EU ETS.

First, the emissions technology implies constant returns to scale in emission abatement (see equation (3)), i.e., there are no scale economies involved in abatement. In that regard, the framework differs from models emphasizing fixed costs for pollution abatement (such as Forslid *et al.* 2018). Since there are no economically viable end-of-pipe technologies to abate carbon emissions, emissions abatement occurs either through saving energy (i.e., by increasing efficiency) or through switching fuels (which does not necessarily come with high fixed cost). Therefore, the importance of fixed cost for carbon abatement is not clear.

Second, firm-level productivity is fixed. The model abstracts from firm-level productivity improvements induced by technical change or regulation. While restrictive, this assumption is in line with recent evidence on technology lock-in of US manufacturing plants from the first year of operation (Hawkins-Pierot and Wagner, 2022). The overall productivity level of a country can still adjust by virtue of changes in the productivity threshold at which firms decide to produce.

Third, the parameters for productivity dispersion ($\theta_s$), emission elasticity ($\alpha_s$) and elasticity of substitution ($\sigma_s$) are assumed to be constant over time and across countries. Given the rather short period of our analysis (2005-2019), the former assumption does not seem controversial, while the latter merits further discussion. We check the plausibility of this assumption by comparing our parameter estimates to those in Shapiro and Walker (2018). Our parameters display similar patterns across sectors and are of a comparable magnitude. The fixed cost for drawing a productivity is assumed to be time-invariant.

In equilibrium, labour markets clear in each country $i$. Note that labour in this model is used for five purposes: paying the fixed cost for drawing a productivity, production and abatement, paying emission taxes, paying market entry costs, and paying for net exports.[5] While labour can freely move across these purposes, total labour demand has to equal labour supply which is provided inelastically. Also, in equilibrium, the fixed cost of drawing a productivity is equal to the expected profits from doing so. This is known as the Free-Entry-Condition in the context of Melitz trade-models. The equilibrium conditions are formally stated in the Appendix in equations (15) and (16).

[5]The latter is required because trade imbalances, in this static model, constitute a transfer between trading partners.

Integrating over the mass of operating firms allows us to calculate total country-level emissions and bilateral trade flows. Specifically, carbon emissions of country $i$ in sector $s$ are given by:

$$Z_{i,s} = \frac{w_i}{t_{i,s}} M^e_{i,s} f^e_{i,s} \frac{\alpha_s \theta_s}{(1-\alpha_s)} \tag{4}$$

In this equation, $M^e_{i,s}$ represents the mass of entering firms, and $f^e_{i,s}$ the fixed cost for drawing a productivity.

For the emissions development, a variety of channels play a role. At the firm-level, emissions depend on the abatement level chosen by firms. More productive firms will generally abate more (which can be seen from Equation (14) in the Appendix), as they charge lower prices which drives up the ratio of emission taxes to output prices. Higher emission taxes also induce firms to abate more. At the sector-level, it also matters how production is allocated among producers of varying emission intensity. For that reason, changes in trade cost matter for the emissions development: At lower trade cost, e.g., the threshold productivity above which firms find it profitable to produce shifts up, thereby reallocating production towards more productive producers and hence affecting emissions. These changes are reflected in firm entries $M^e_{i,s}$.

We rewrite the model in changes applying the hat-algebra by Dekle *et al.* (2008) to facilitate quantification. Hence, all variables are expressed as a change ($\hat{x}$) relative to a baseline ($x$). Through this reformulation several variables that are hard to measure drop out of the model. In our quantitative exercise, we use the year 2005 as a baseline and rewrite all variables of interest as changes relative to that base year. Using this model reformulation, changes in emissions for country $o$ are represented by:

$$\hat{Z}_o = \frac{\sum_s \frac{\hat{M}^e_{o,s} \hat{w}_o}{\hat{t}_{o,s}} Z_{o,s}}{\sum_s Z_{o,s}} \tag{5}$$

Sectoral emissions increase proportionally with firm entry $M^e_{o,s}$ and wages and decrease with regulation. The model implies that changes in wages and firm entries are functions of changes in country- and sector-level revenues, respectively. In essence, the change in sector-level emissions depends on three factors: the development of climate regulation, overall growth of the economy, and relative growth of different sectors.[6] The equation

[6]More accurately, the change in wages is equal to the change in country-level revenues, and changes in firm entries are given by the (revenue) growth of a sector relative to the average growth of the economy.

can also be interpreted as directly following from the assumed Cobb-Douglas production function: In each sector, the change in the optimal ratio of inputs (emissions to labour, captured by the change in sector-level firm entries) depends on the change in the input cost (wages to emission taxes).

We calibrate the model and use model relations to recover the historical development of different emission drivers. The idea is to back out how different drivers in the model must have developed in order for the model to generate the trade and production patterns across countries that were actually realised. That is, given the model structure and our parameters, how must, e.g., the implicit price on carbon emissions faced by firms in different sectors, $t_{o,s}$, have developed in order to rationalise the observed outcomes in terms of trade, production and emissions? We follow Shapiro and Walker (2018) and define five types of emission drivers of interest. We then track their impact on emissions development:

- Expenditure share driver: changes in $\beta_{i,s}$. Captures changes in the across-sector allocation of expenditures on the side of consumers (see Equation (1)).

- Regulation driver: changes in $t_{i,s}$. Captures changes in the implicit price on carbon emissions faced by firms in country $i$ and sector $s$. $t_{i,s}$ is obtained by rearranging model Equation (5): $\hat{t}_{i,s} = \frac{\hat{M}^e_{i,s}\hat{w}_i}{\hat{Z}_{i,s}}$. Since calculating the development of implicit carbon prices requires data on sector-level emissions, we are only able to calculate $t_{i,s}$ for countries for which reliable emissions-data are available. Specifically, we calculate and contrast the change in implicit carbon prices for Germany and the rest of the EU. This implicit carbon price reflects all factors that somehow put a price on carbon emissions, i.e., energy prices, carbon taxes as well as command-and-control instruments.

- Competitiveness driver (net of regulation): This driver confounds a multitude of different factors and captures changes in productivity of country $o$, $b_{o,s}$, as well as trade costs, $\tau_{oi,s}$ and $f_{oi,s}$. We do not separate these components. The driver is a capture-

This results from the fact that the model features one production factor only, so that all revenue changes must be reflected in wage adjustments. Real wages are determined by country growth relative to all other countries.

all term comprising different variables related to competitiveness. Specifically, the driver is defined in the following way: $\hat{\Gamma}^*_{od,s} \equiv (1/\hat{b}_{o,s})^{-\theta_s}(\hat{\tau}_{od,s})^{-\frac{\theta_s}{1-\alpha_s}}(\hat{f}_{od,s})^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}}$

- Competitiveness driver (including regulation): equivalent to the competitiveness driver above for the foreign country $d$, but additionally comprising changes in climate regulation $t_{d,s}$ that cannot be recovered separately for data reasons: $\hat{\Gamma}^*_{do,s} \equiv (1/\hat{b}_{d,s})^{-\theta_s}(\hat{\tau}_{do,s})^{-\frac{\theta_s}{1-\alpha_s}}(\hat{f}_{do,s})^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}}(\hat{t}_{d,s})^{-\frac{\alpha_s\theta_s}{1-\alpha_s}}$. This is what we calculate for the rest of the world.

- Trade imbalance driver: This driver is required so that the static framework can exactly match historic production and expenditure data. Trade imbalances in the model are taken from the data and appear as transfers between countries.

The exact measurement of the (less straightforward) competitiveness driver is shown in the Appendix. Note that drivers vary across sectors which is more realistic than having emission drivers affect the whole economy in the same way at the same time.

Plugging in production and trade data as well as parameter estimates for $\sigma_s$, $\alpha_s$ and $\theta_s$, we can calculate the historical developments of emission drivers implied by the model. Specifically, we are able to accurately calculate the expenditure share, domestic regulation, and trade imbalance drivers. Calculation of the competitiveness drivers would require data on price indices that are not available, and our calculated competitiveness drivers are net of this component. As in the original paper by Shapiro and Walker (2018) this implies that the development in competitiveness drivers is hard to interpret. The calculated drivers can however still be used to calculate counterfactual emissions as the price indices cancel out in the equilibrium conditions where they appear.

In a second step, we disentangle how important these historic developments have been in shaping German industrial emissions in relative terms. To do so, we allow all emission drivers to follow their historical path except for one, which is set to 1 (assuming it remained as in 2005). We plug these alternative values for emission drivers into the model and solve the model numerically, finding the changes in wages ($\hat{w}_{is}$) and firm entries ($\hat{M}^e_{is}$) that make the equilibrium conditions (equations (17) and (18) in the Appendix) hold with equality for all countries, sectors and years.[7] The values backed out by the algorithm can then be used to calculate the emissions associated with the endogenous firm-level decisions on entry, exit, abatement, production and exports under the analysed scenario according to Equation (5). Importantly, those counterfactual emissions incorporate general equilibrium forces. Comparing the counterfactual emissions with the actual emissions development helps understand how important a given emissions driver has been for emissions development, and in which direction it has worked.

Lastly, we use the model for counterfactual analysis and examine how the German industrial emissions would have developed if the regulation drivers in Germany and the rest of the EU, i.e., the implicit price on carbon emissions, had developed identically over the period.

# 3 Data and parameter estimation

## 3.1 Data

Quantification of the model requires two sets of ingredients: First, we need values for a set of model parameters that govern fundamental model relationships. Second, we need information on model outcomes in terms of trade and production values as well as emissions. These two data inputs allow us to back out the values different emissions drivers must have taken on, given the parameter values, for the model to generate the outcomes (i.e., production volumes, trade values, CO2 emissions) that were actually realised. In the following, we briefly describe the data sets used, while Section 3.2 discusses the estimation procedure for the different model parameters in detail.

All parameter values are estimated using firm-level data from the official German Manufacturing Census. Participation in the surveys on which the Census is based is mandatory. Generally, the Census covers all German manufacturing plants with at least 20 employees, though different thresholds apply for select Census modules. We have annual data available from 1998 to 2017. For the estimation of our three parameters we

[7]The model is solved numerically using a trust-region-reflective algorithm. We constrain the endogenous variables to take on positive values. Plugging historic values into the model for all emission drivers recreates the actual historic development of emissions.

use information on firm-level revenues, energy use, emissions, capital stocks, and costs.[8] All Census data are taken from our base year 2005.[9]

Sector-level emissions for Germany and the EU are taken from the IEA (2022a) for the period 2005 to 2019. Emissions data include indirect emissions from electricity consumption.[10] Note that accurate emissions data at the sector-level are not available for the rest of the world outside of the EU. For this reason, we only separate the climate regulation driver from the general competitiveness driver in the case of Germany and the EU. For the rest of the world, changes in implicit carbon prices are subsumed under the competitiveness driver.

Production data in manufacturing across the world are taken from the United Nations Industrial Development Organization (2022). The INDSTAT database contains output (in million dollars) disaggregated at the 2-digit sector-level of the International Standard Industrial Classification of All Economic Activities (ISIC) for 174 countries (though exact coverage differs across years). Data are available from 1963 to 2020, but we focus on

[8]While the Census itself does not contain information on plant-level emissions, it requires plants to report their consumption of 14 different fuels plus electricity. We combine the information on fuel consumption with emission factors from the German Federal Environmental Agency (Umweltbundesamt, 2008, 2020a,b) to convert fuel consumption into carbon emissions.

[9]Choosing 2005, i.e., the year of the introduction of the EU ETS, as a base year might seem an odd choice. Using an earlier base year one could in principle analyse how large the increase in climate policy stringency through the EU ETS was. In reality, however, we are unlikely to be able to realistically disentangle this effect for the following reasons: First, firms had expectations about carbon prices in the future that might already play into their emissions and abatement behaviour before the ETS coming into effect. Second, grandfathering of free permits in the EU ETS might have incentivised firms to artificially increase their emissions prior to the ETS introduction. Suggestive evidence for such rent-seeking has been found, e.g., in France by Colmer *et al.* (2023). The IO tables we use are not available prior to 2005. The energy statistics in the German Manufacturing Census are also less reliable prior to 2005 due to a change in the reporting. Given these challenges, we chose 2005 as our base year.

[10]While we can calculate carbon emissions from German manufacturing also from the Census data, the IEA data has the advantage of providing a greater coverage, both in terms of time (we only have Census data available between 2005 and 2017), and in terms of countries. However, there are some differences in sector-level emissions for Germany over the two data sets. Among others, they exhibit different trends since 2005: According to the Manufacturing Census, carbon emissions increased between 2005 and 2017, while they exhibit a generally decreasing trend according to the IEA. Differences are discussed in more detail in the Appendix. Qualitatively, however, we obtain similar results from quantifying the model with either of the two data sources, as shown in the Appendix.

the years 2005 to 2019 for which all other data sets are available too. We merge very small sectors, and aggregate sectors to achieve a consistent sector classification across the different data sets. This procedure yields 11 different manufacturing sectors in our analysis. Their respective NACE sector codes alongside with a short description are provided in Table 1. Given the European focus of the analysis, we convert dollar values to Euros, using exchange rates from the OECD (2022). Lastly, since we quantify the model presented in Section 2 in a three-country environment, we aggregate production data to three world regions: Germany (DE), the rest of the EU (EU), and the rest of the world (ROW).[11]

Table 1: Analysed NACE 2 sectors

| **NACE 2 Code** | **Description** |
|---|---|
| 10 to 12 | Food, tobacco and beverages |
| 13 to 15 | Textiles, wearing apparel, fur, leather and footwear |
| 16 | Wood products |
| 17 and 18 | Paper, paper products, printing and publishing |
| 19 | Coke and petroleum |
| 20 and 21 | Chemicals, chemical products and pharmaceuticals |
| 22 | Rubber and plastic products |
| 23 | Non-metallic mineral products |
| 24 | Basic metals |
| 25 to 28, 33 | Fabricated metals, electronic products, electric equipment, machinery and installation |
| 29 to 32 | Vehicles, vehicle components, other transport, manufacturing n.e.c. |

Trade data are provided by Eurostat (2023a). Specifically, we extract German and EU-level import and export values in Euros.[12] To correct data for re-exports (i.e., exports where the exported goods have not been produced in the exporting country), we use information on annual imports that are re-exported at the sectoral level from input-

[11]We assign countries consistently to one group (EU or ROW), discarding changes through EU accessions.

[12]While the combination of trade and production data on a sectoral level is inherently difficult due to fundamentally different underlying classifications, the Eurostat data is reported in a classification that can be directly related and merged to NACE codes.

output tables by Germany and the EU (Eurostat, 2023b). These are subtracted from the German, the EU and the ROW import and export values.[13,14]

Lastly, to better understand the drivers behind the development in implicit carbon prices faced by firms, we collect data on country-level fuel prices and fuel mixes from the IEA (IEA 2022b and IEA 2022a), on ETS coverage of different sectors from the European Union's transaction log, average annual ETS permit prices from Statista, and on the emission intensity of electricity generation from the EEA.[15,16] All these data are available for the time period between 2005 and 2019.

The data and its level of aggregation have important implications for the scope of the analysis that are worth discussing in more detail. First, in contrast to Shapiro and Walker (2018), we treat the quantitative model as a three-country world, distinguishing between Germany, the rest of the EU and the rest of the world. We do so to account for Germany's embeddedness in the European Union with the single market and common climate policy shocks (e.g., through the EU ETS). The distinction of two groups of trading partners is interesting for several reasons: Distinguishing between Germany and the EU allows us to uncover the development of implicit carbon prices in both regions. While the EU has a common climate policy instrument with the EU ETS, substantial national autonomy remains in terms of setting the stringency of climate regulation for each country, which

[13] The issue is that while re-exports are reflected in the trade data both as imports and as exports, they are not counted in production data. Re-exports can be substantial. Quantification of the model requires us to calculate shares of worldwide production that are produced and consumed domestically, produced domestically but exported, and consumed domestically but imported. To ensure these measures are accurate and exports cannot be larger than production, we need to correct trade-numbers downwardly to account for re-exports. Details on the correction we apply can be found in the Appendix.

[14] We also check trade and production data in Germany against numbers from the German Manufacturing Census. Graphs displaying these comparisons are available in the Appendix and reveal that levels and trends are similar in the final data. Moreover, we compare the (gross) output data from INDSTAT with country-level manufacturing GDP from the Worldbank. The countries contained in the INDSTAT data cover roughly 94-96% of worldwide GDP as reported by the Worldbank (depending on the year). Coverage of our analysis is hence large. The ratio of manufacturing GDP (from the Worldbank) to gross output (from INDSTAT) generally is around 30% in the median and falls well in the range of what is reported by Dekle *et al.* (2008) (at the country-level).

[15] The EEA calculates these intensities with the help of national emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism and Eurostat energy balances (nrg_bal_c).

[16] The Statista permit prices can be found under the following address: https://de.statista.com/statistik/daten/studie/1304069.

we will discuss in greater detail in Section 4. Contrasting implicit carbon prices for Germany and the rest of the EU, we can show how large differences in the developments of regulation have actually been, and whether we can in fact speak of a single climate policy of the EU. Unfortunately, the lack of available data on global industrial carbon emissions at the sectoral level prevents us from quantifying the development of climate policy stringency for the rest of the world. Also, separating the rest of the world (from a German perspective) into a group of countries that is very much integrated and a group of countries that is not allows us to assess the importance of market and policy integration with other countries for the development of domestic carbon emissions.

Second, the sector classification used has important implications in terms of what the model recovers as (what type of) emission driver. Specifically, the model focuses on within-sector changes and does not feature endogenous substitution across sectors. Changes in the relative importance of different sectors will be reflected as changes in the Cobb-Douglas exponents $\beta_s$. Using a rather broad sector classification means that composition shifts within sectors will not be treated as expenditure share changes. Any emission development coming from within-sector composition shifts in contrast will be captured by one of the other emission drivers. Conducting the analysis at a smaller sectoral level would yield a more accurate picture in that respect, but come at the cost of introducing more noise: Production and trade data at the 3-digit sector-level, while available, are substantially more volatile. Even at the 2-digit level, small sectors such as tobacco production or printing and publishing display unreasonably large variation in their production and trade patterns. Similarly, using a more fine-grained sector classification would allow production technologies to differ at a smaller sectoral scale and impose less restrictions on the homogeneity of production within 2-digit sectors: The responsiveness of emissions to abatement ($\alpha_s$) could display heterogeneity within 2-digit sectors. Acknowledging these issues, we conduct our analysis on the 2-digit sector level for the lack of more disaggregated emissions-data as well as input-output tables.

## 3.2 Parameter estimation

Parametrization of the model requires the estimation of three distinct model parameters: the Pareto shape parameter $\theta_s$, the elasticity of substitution $\sigma_s$ and the elasticity of emission intensity with respect to abatement intensity $\alpha_s$. In the following, we briefly describe the estimation of each of these parameters.

To estimate the Pareto shape parameter, we rely on the fact that a Pareto distribution of firm productivities implies that firm revenues too follow a pareto distribution with the shape parameter $\theta_s/(\sigma_s - 1)$. Therefore, we can learn about the underlying shape parameter of the productivity distribution by studying the revenue distribution of firms. Specifically, we follow Gabaix (2009) and recover the shape parameter of the revenue distribution in each sector by regressing the log of a firm's revenue rank on the log of its revenues. We then use the estimate to calculate $\theta_s$ by multiplying with $(1 - \sigma_s)$. Firm-level revenues are taken from the German Manufacturing Census. We run the regressions for 2005. As suggested by di Giovanni *et al.* (2011) we only use domestic revenues (without exports) in the regression to rule out bias owing to the selection into exporting. Moreover, following previous literature (Gabaix, 2009; di Giovanni *et al.*, 2011), we limit our sample in the estimation of the Pareto shape parameter to firms in the upper decile of the revenue distribution since the Pareto distribution best fits the right tail of the firm distribution.[17] To reduce bias, we subtract one half from the sales rank before taking the log, as proposed by Gabaix and Ibragimov (2011). Generally, estimates are close to negative 1, as predicted by Zipf's law.

To obtain sector-level elasticities of substitution between varieties within a sector, we follow prior literature and measure markups from the data by taking the ratio of revenues and variable cost for the different sectors in 2005 (see, e.g., Shapiro and Walker 2018, Antras *et al.* 2017 or Hsieh and Ossa 2016). Then we back out the elasticity of substitution that rationalises these markups, given the imposed market structure: $\sigma_s = (1 - \alpha_s)/((1 - \alpha_s) - \mu_s)$, where $\mu_s$ constitutes the markup.[18] We follow Blaum *et al.* (2018) and measure markups by taking the ratio of firm-level total revenues and the sum of materials and labour expenditure plus 0.2 times the capital stock to proxy for

[17] We conduct visual checks to ensure that indeed, for these firms, the relationship between firm rank and size is approximately linear.

[18] Specifically, the model implies $w_o L^p_{o,s} = (1 - \alpha_s) \frac{\sigma_s - 1}{\sigma_s} R_{o,s}$, with $L^p_{os}$ as the labour used in production and $R_{o,s}$ revenues in sector $s$ and country $o$.

the user cost of capital.[19,20] With this procedure, we calculate markups of roughly 38% as an (unweighted) average across German industrial sectors in 2005, which is well in line with the estimate of 35% for Germany by de Loecker and Eeckhout (2018).

To recover the elasticity of emission intensity with respect to abatement intensity, $\alpha_s$, we leverage the fact that in the model, this elasticity also constitutes the output elasticity of emissions in the firm's production function (see Equation (3)). In a first step, we compute the output elasticity of energy by applying the factor share approach, i.e., by taking the energy cost share from revenues, as discussed by Syverson (2011). In a second step, we divide this elasticity by an estimate of the elasticity of carbon emissions to energy use, to get from an energy to an emissions output elasticity. The formal relationship between the two output elasticities is shown in equation (6), where the left hand side of the equation represents the definition of the output elasticity of emissions, and $e$ denotes energy input:

$$\frac{\partial q}{\partial z}\frac{z}{q} = \frac{\partial q}{\partial e} \times \frac{\partial e}{\partial z}\frac{z}{q} = \frac{\frac{\partial q}{\partial e}}{\frac{\partial z}{\partial e}}\frac{e}{q}\frac{z}{q}\frac{q}{e} = \frac{\frac{\partial q}{\partial e}\frac{e}{q}}{\frac{\partial z}{\partial e}\frac{e}{z}} \tag{6}$$

The factor share approach to retrieve the output elasticity of energy (numerator in Equation (6)) follows from static cost minimisation. Generally, such simple index measures of output elasticities have been found to perform quite well (Biesenbroeck, 2007). As discussed in de Loecker and Syverson (2021), output elasticities retrieved from this approach might however be misspecified if there are factor adjustment cost. These are arguably low in the case of energy (as compared to, e.g., labour). Still, to minimise any bias, we take sector level averages to smooth out idiosyncratic misalignments due to firms operating away from their long-run desired input level. We adjust the calculated output elasticity of energy for the emission intensity of sector level fuel mixes. We estimate the elasticity of carbon emissions to energy use separately for each sector in 2005 using log-log regressions of emissions on energy use at the firm level (denominator of equation (6)).

Our parameter estimates are summarised in Table 2. More details on the parameter estimation can be found in Appendix 8.5.

[19] Capital stocks are calculated via the perpetual inventory method, following Lutz (2016).

[20] This approach helps to operationalise the model-based prediction $w_o L^p_{o,s} = (1-\alpha_s)\frac{\sigma_s - 1}{\sigma_s} R_{o,s}$, with $L^p_{os}$ reflecting labour input used for production, by eliminating cost components from the measurement of total input cost $w_o L^p_{os}$ that are clearly not productive, such as marketing cost.

Table 2: Estimated parameter values

| NACE 2 Code | | $\theta_s$ | $\sigma_s$ | $\alpha_s$ |
|---|---|---|---|---|
| 10 to 12 | food, tobacco, beverages | 2.102 | 2.512 | 0.020 |
| 13 to 15 | textiles, wearing apparel, leather | 7.124 | 4.442 | 0.019 |
| 16 | wood products | 6.442 | 4.767 | 0.038 |
| 17 and 18 | pulp, paper, publishing | 16.871 | 10.270 | 0.058 |
| 19 | coke, petroleum | 0.797 | 1.767 | 0.009 |
| 20 and 21 | chemicals, pharmaceuticals | 2.605 | 3.101 | 0.041 |
| 22 | rubber, plastics | 5.483 | 4.323 | 0.024 |
| 23 | non-metallic minerals | 6.841 | 4.563 | 0.078 |
| 24 | metals | 8.187 | 7.396 | 0.063 |
| 25 to 28, 33 | metal products, electronics, machinery | 7.063 | 6.194 | 0.010 |
| 29 to 32 | vehicles, other transport, n.e.c. | 5.147 | 6.133 | 0.008 |

Our estimates of $\theta_s$ describe the dispersion of productivity in the sector. Sectors such as the food or chemicals sector are relatively heterogeneous (small $\theta$), whereas sectors such as paper products, basic metals and textiles and apparel are in the bottom three with regard to heterogeneity (large $\theta$). In the US case, Shapiro and Walker (2018) find the basic metals sector also to be very homogeneous, but the other two sectors in bottom three are wood products, and coke and refined petroleum.[21] In terms of magnitude our estimates are generally fairly similar. As expected, elasticities of substitution are generally lower for sectors with arguably differentiated products (food, chemicals) and higher for sectors in which products are more homogeneous (printing and reproduction of media, basic metals). Here results are very similar to parameters recovered by Shapiro and Walker (2018) for the US. With regard to $\alpha_s$ the estimates in Shapiro and Walker (2018) refer to local pollutants, whereas our $\alpha_s$ concerns carbon emissions. These pollutants are different also in terms of abatement opportunities. Nevertheless, we see similar patterns with regard to the most polluting sectors: Basic metals, non-metallic mineral products, paper products and chemical products have the highest output elasticity of emissions in both applications.

[21]Several of the sectors are not directly comparable because data limitations required us to constrain our model to just 11 sectors, whereas Shapiro and Walker (2018) have 17 different manufacturing sectors.

# 4 The development of implicit carbon prices in Germany and the EU

## 4.1 Historical developments of emission drivers

Exploiting the imposed model structure in combination with the data and parameters described above allows us to recover historical developments of emission drivers. We focus the discussion on the development of implicit carbon prices. As mentioned earlier, the historical values of the competitiveness drivers are not meaningful for interpretation. The historical expenditure share developments are shown in Appendix 9.

The climate regulation drivers capture how the implicit price on carbon emissions must have developed in each country and each sector in order to rationalise the emissions, production values and trade patterns observed, given the imposed model structure. This implicit carbon price entails all factors that somehow affect the price of carbon emissions, such as carbon prices under the EU ETS, fuel prices or command-and-control measures.

The left panel of Figure 1 shows the development of the implicit stringency of climate regulation in the German manufacturing sector as compared to base year 2005. Regulation drivers are generally sector-specific and the graph shows simple averages across sectors.[22] Averages are depicted separately for sectors mostly covered by the EU ETS (NACE 17+18: pulp, paper and publishing, NACE 19: coke and petroleum; NACE 20+21: chemicals and pharmaceuticals; NACE 23: other non-metallic mineral products and NACE 24: metal production), versus the remaining sectors. Both sector groups however follow similar trends with respect to the implicit carbon price faced by firms: Specifically, the stringency of climate regulation decreased substantially for both ETS and non-ETS regulated sectors between 2005 and 2017, by 38.8% and 21.6% respectively. Qualitatively, this decrease mimics the development of carbon prices under the EU ETS, which on average decreased by even 73% from its introduction in 2005 to 2017, as shown in Figure 2. In 2018 and 2019, the implicit carbon price increased, again in line with the development of permit prices under the EU ETS. However, while for non-ETS sectors, the implicit price on carbon emissions in Germany was slightly higher in 2019 than in 2005, for ETS sectors, it remained at considerably lower levels.

[22]Sector-level regulation drivers are reported in the Appendix.

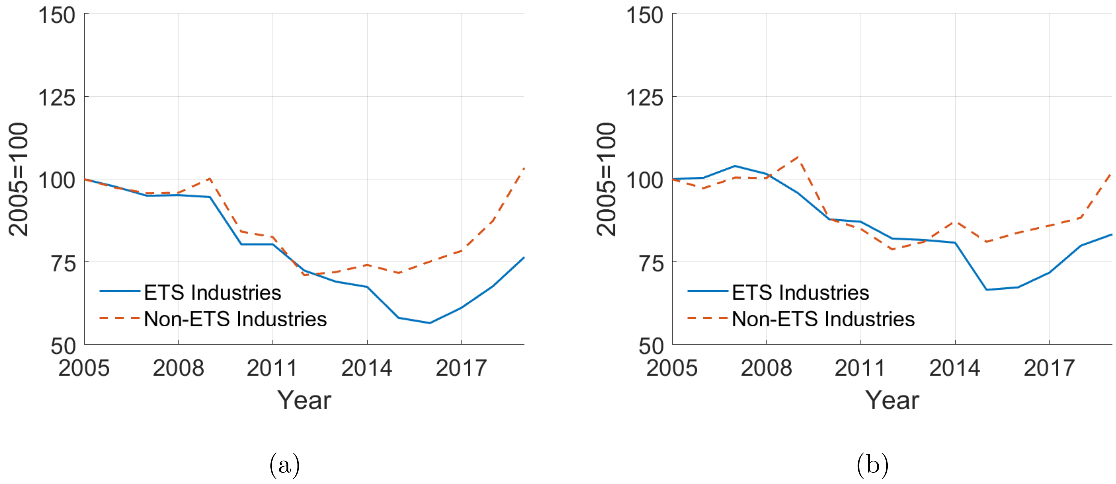



Figure 1: Development of implicit price on carbon emissions (a) in Germany (left) (b) for the rest of the EU (right)

The right panel of Figure 1 shows that the development in the rest of the EU is qualitatively similar, albeit a bit weaker, and with an initial increase in implicit carbon prices for ETS-sectors after the introduction of the EU ETS.

The general decrease in the stringency of climate regulation might seem unsurprising given the decrease in allowance prices under the EU's main climate policy instrument. However, it is still notable for the following reasons: First, the decrease in climate policy stringency is not only visible for the sectors in which large parts of carbon emissions are covered by the EU ETS, but also in the less emission intensive sectors. A possible explanation for the similar developments across sectors is that ETS-covered (manufacturing) firms pass on the costs incurred under the EU ETS as suggested in Hintermann *et al.* (2020) or Hintermann (2016), such that sectors not covered by the EU ETS are in fact treated indirectly. In particular, passthrough of ETS cost in electricity generation means that electricity using manufacturing firms are exposed to the ETS price. Moreover, carbon prices under the EU ETS are not the only factor that the regulation driver depicted above capture: By rationalising the emissions development (given the model structure), the model-based decomposition backs out an implicit carbon price reflecting also the development of energy prices and command-and-control regulation that affect the shadow price of carbon emissions. The latter might include, e.g., the promotion of renewable energies and CHP, technology standards under the large combustion plant directives, emission reporting requirements introduced by the E-PRTR or the introduction

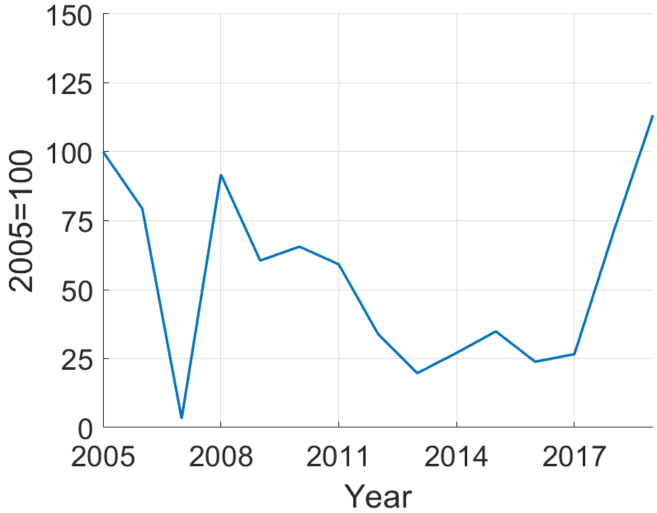



Figure 2: Development of average carbon prices under the EU ETS between 2005 and 2019, indexed to 2005

Based on: Statista (2022); https://de.statista.com/statistik/daten/studie/1304069

of the requirement to set up energy management systems or to conduct energy audits for certain companies. Our measure can express how the stringency of these overlapping regulations overall developed.

## 4.2 Explaining developments in implicit carbon prices

How much of the decrease in the implicit carbon price is driven by decreasing prices under the EU ETS as opposed to changes in fuel prices and command-and-control measures? We disentangle the relative importance of these different developments by means of a simple regression analysis. Specifically, we estimate the following equations:

$$\hat{t}_{i,s,t} = \beta_f \hat{p}^{energy}_{i,s,t} + \beta_{ets} \hat{p}^{ets}_{i,s,t} + \mu_{i,t} + \epsilon_{i,s,t} \tag{7}$$

$$\mu_{i,t} = \gamma_{ets} \hat{p}^{ets}_{i,t} + \psi_{i,t} \tag{8}$$

Due to the availability of sector-level emissions data we can recover the development of $\hat{t}$ for both the EU and Germany, $i \in \{DE, EU\}$. Subscript $t$ denotes the years of the sample between 2005 and 2019. $p^{energy}_{i,s,t}$ reflects energy prices faced by sector $s$ in country $i$ at time $t$. While industrial fuel prices do not vary across sectors in a given country-year combination, variation across sectors is introduced by the different fuel mixes used. The coke and petroleum sector, e.g., uses a high share of oil and is therefore more exposed to oil price developments as compared to other sectors. Similarly, $p^{ets}_{i,s,t}$ captures the effective carbon price under the EU ETS faced by different sectors. Since the EU constitutes a single carbon market, the ETS-price in principle only displays variation over time. However, sector- and country-level variation emerges from sectors/countries using fuel mixes with varying emission intensity, as well as from sectors being covered to a different extent under the EU ETS in different countries and at different times. Due to the inclusion threshold of 20 MW in the industrial sector, not all emissions from a given sector are regulated. $p^{ets}_{i,s,t}$ captures those differences by reflecting the price in EUR/kWh that effectively had to be paid on average in a certain sector, country, and year, given the emission intensity of the fuel mix and the ETS coverage.[23] Both the development of energy prices for different sectors and de facto ETS-prices are shown in the Appendix. General developments in EU ETS and energy prices as well as national cross-sectoral command-and-control measures are captured by the country-by-year fixed effects $\mu_{i,t}$. We decompose this fixed effect in a second regression to separate the impact of the EU ETS on the implicit carbon price from national regulation ($\psi_{i,t}$). Any other command-and-control measure that varies by country, sector and year is contained in the error term $\epsilon_{i,s,t}$. We abstain from clustering standard errors at the sector-level due to the low number of clusters (Cameron and Miller, 2015). As the dependent variable is an index (equal to 1 in base year 2005), we also transform our explanatory variables $p^{energy}_{i,s,t}$ and $p^{ets}_{i,s,t}$ into indices – i.e., we explain the *development* in implicit carbon prices by the *development* in energy and fuel prices. The transformation has a similar, albeit not identical, effect to using sector fixed effects. Results are shown in Table 3.

Clearly, as shown in column (1), energy prices have a strong impact on the implicit price for carbon. A doubling of energy prices as compared to 2005 (i.e., an increase in a sector's energy price index by 1) is associated with an increase in implicit carbon prices of 28 percentage points. Carbon prices under the EU ETS are not statistically significant when identified from sectoral variation, indicating that the main effect of the ETS is captured by the time fixed effect. This is confirmed in Column (2), which shows a highly significant relationship between the two variables indicating that carbon prices under the

[23]Implicitly, we are assuming that the ETS covered installations in any sector use the same fuel mix as those firms not directly regulated under the EU ETS.

Table 3: Determinants of the development of implicit carbon prices

| | $\hat{t}_{i,t,s}$ | $\mu_{i,t}$ |
|---|---|---|
| | (1) | (2) |
| $\hat{p}^{energy}_{i,s,t}$ | 0.278*** | |
| | (0.074) | |
| $\hat{p}^{ets}_{i,(s),t}$ | -0.001 | 0.251*** |
| | (0.015) | (0.022) |
| $N$ | 330 | 330 |
| $R^2$ | 0.49 | 0.28 |

Notes: The regressions include observations from 2005–2019. Dependent variables are indexed and are 1 in 2005. The regression in column (1) is run with country by year fixed effects. Column (2) explains the fixed effect estimated in column (1). Standard errors are displayed in parentheses. *, ** and *** indicate significance at 10%, 5% and 1%, respectively.

EU ETS play a role in the regulation driver similar to that of energy prices.[24] This effect captures both the direct effect of the EU ETS on manufacturing firms, and the effect of rising electricity prices to the extent permit prices might have been passed on by the power sector, as suggested by Fabra and Reguant (2014) and Hintermann (2016).

## 4.3 Differences in implicit carbon prices between Germany and the EU

As shown in Figure 1, implicit carbon prices follow a similar trend in Germany and the EU. The same holds true for the non sector-specific region-by-year component of the regulation driver, depicted in Figure 3. The common trend makes sense given the common

[24]Note that in our observation period, permit prices under the EU ETS have not monotonically increased or decreased. Therefore, it is reassuring in terms of the informative value of our model that we find a strong relationship between the country-by-year fixed effects and permit prices. These are not simply driven by both factors continuously going up or down. In fact, plotting the predicted $\mu_{i,t}$ from the regression shows a pattern over time that is very similar to the development of permit prices under the EU ETS, as shown in Figure 3.

policy framework within the EU: The EU ETS applies to all member states. The same is true for many command-and-control measures. The Large Combustion Plant (LCP) Directive (2001/80/EC), e.g., sets technology standards and emission limits (for local pollutants) for large combustion plants with a capacity of more than 50 MW throughout the EU. Emissions reporting requirements under the E-PRTR too have to be satisfied by all member states (regulation no. 166/2006).

Yet, the implicit carbon prices we back out from the model differ in one important aspect between EU and Germany: Our findings indicate that the stringency of German climate regulation has declined at a steeper rate than in the rest of the EU compared to its 2005 level. This finding holds both in the ETS and in the non-ETS industries. Note that we are silent on the absolute level of regulatory stringency. It could be that Germany started out with more stringent climate policy than other EU countries, e.g., through higher energy prices or environmental standards. In that case, our results imply a convergence of German policy toward the climate policy stringency of the rest of the EU. In any case, are such different developments reasonable given the many common policies in place in the EU? At least four explanations come to mind:

First, the common European policy framework leaves leeway for the member states in terms of the exact policy implementation. In case of the EU ETS, e.g., member states decided on the amount and rules for allocating emission allowances through national allocation plans prior to phase 1. While the plans were checked by the European Commission, this decentralised approach arguably led to cross-country differences in climate policy stringency within the EU. Further, the member states have the opportunity to compensate firms in certain sectors for electricity price increases due to the ETS. While most member states make use of this opportunity, the exact implementation of the compensation scheme (and the size of eligible sectors) differs across member states.[25] In general, countries are not restricted in exceeding the requirements set by the EU. The UK, e.g., has complemented the EU ETS with a price floor since 2013.

[25] In 2018 Germany spent about 18% of allowance auction revenues on indirect cost compensation, compared to almost 20% in the Netherlands, 32% in France and 29% in Finland. The UK in contrast spent less than 4% whereas Spain spent 12% of auction revenues in the same year. Germany had by far the largest number of beneficiaries in terms of installations (891) followed by France (296) and Spain (151) (EC, 2019).

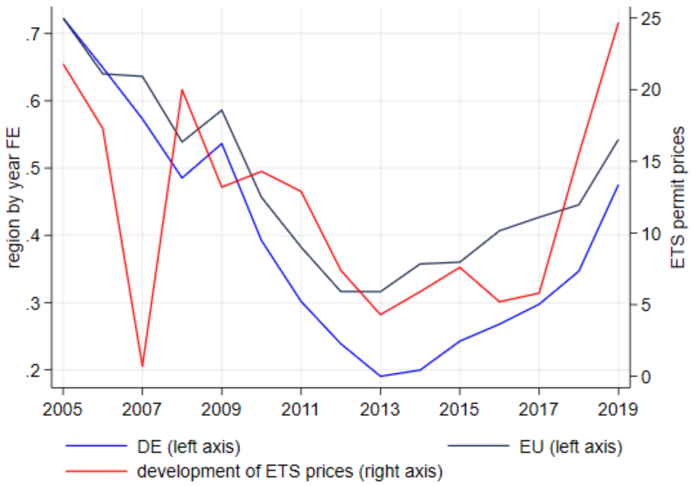



Figure 3: Development of predicted region-by-year fixed effects from explaining the historical regulation driver, and of ETS permit prices

Second, even if the EU member states follow a common policy, the *impact* of that policy may differ across countries. Take the example of the Large Combustion Plant (LCP) directive: The directive set common emission limits for local pollutant emissions ($SO_2$, $NO_x$, dust) from large combustion plants. Across Europe, prior to the LCP, there was substantial variation in the emission intensity of individual plants with plants especially in Eastern European countries being substantially more emission intensive than, e.g., German plants. The LCP directive resulted in large emission reductions in terms of local pollutants especially in the most emission intensive countries (e.g., Cyprus, Estonia, Greece, Romania, Slovenia, Spain – in contrast very little happened in Germany) over the period from 2004 to 2015 (EEA, 2019). These reductions were in part achieved through shutdowns of the most inefficient plants and reductions in the use of coal thus also contributing to reduced CO2-emissions.

Third, member states can also adopt unilateral policies. A prominent example is that Germany has heavily subsidised the expansion of renewable energies under the Renewable Energy Act since 1990. This expansion has reduced the CO2 intensity of the power sector in Germany and thus indirect carbon emissions. The feed-in-tariffs used in this scheme were financed through a surcharge on electricity prices.[26] To reduce the impact on competitiveness of German industrial firms an exemption from paying the Renewable

[26]The German Renewable Energy Surcharge increased from 2 ct/kWh in 2010 to 6.2 ct/kWh in 2014 and peaked at 6.9 ct/kWh in 2017.

Energy Surcharge was introduced for electricity intensive firms and expanded over the period under study. Exemptions from paying electricity grid charges were also expanded for large electricity users in 2011. These exemptions mostly affect the sectors also regulated under the EU ETS. Therefore this policy development – and especially the increase in the renewable energy surcharge over the period – is consistent with the growing split in regulation development between ETS and non-ETS industries in Germany after 2012.

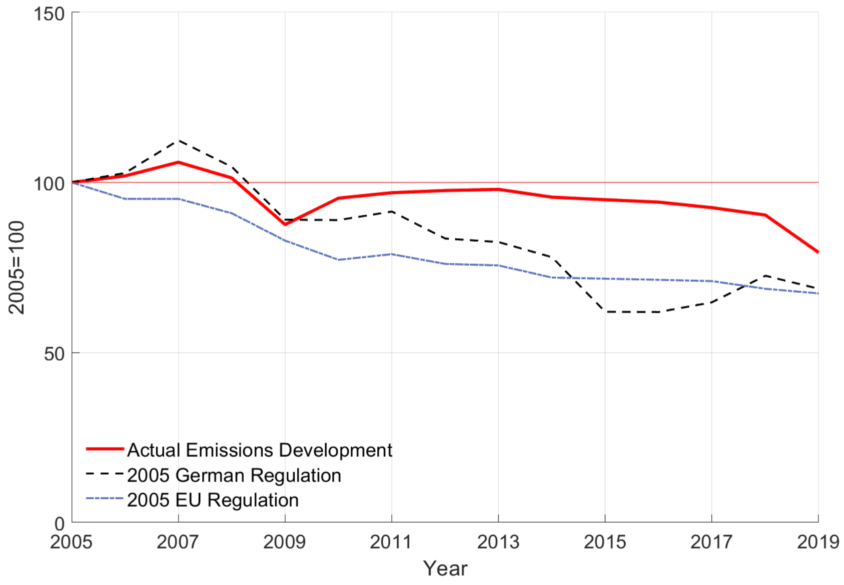
Fourth, industrial energy and electricity prices differ across countries given the fundamentally different energy mixes in the industrial and power sectors: France relies a lot more on nuclear power than Germany, Poland on coal, Estonia on oil, Iceland on renewables, etc. Against this background, the difference in the development of implicit carbon prices between Germany and the rest of the EU seems plausible.

# 5 Counterfactual analysis

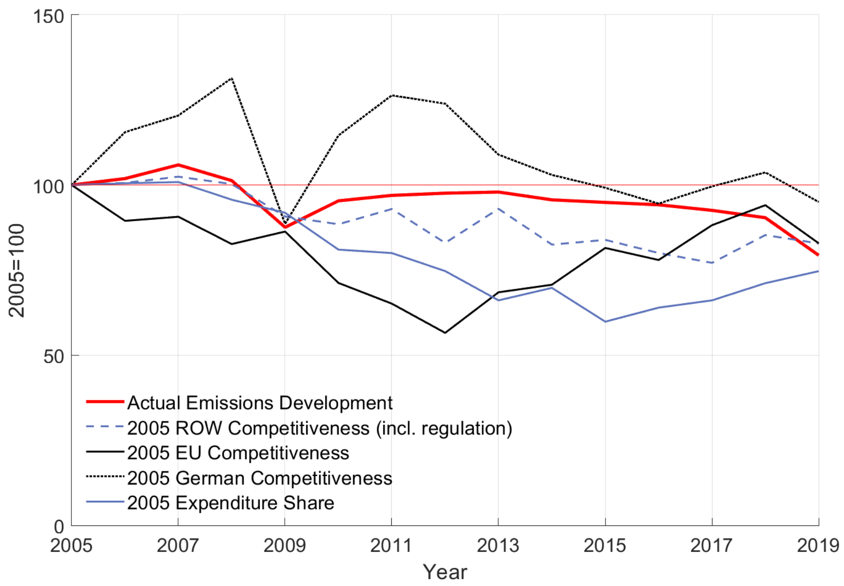
## 5.1 Decomposing carbon emissions in the German manufacturing sector

How important has the decrease in the implicit price on carbon been for the emissions development in German manufacturing? How significant is the divergence in the development between European and German climate policy in shaping German industrial emissions? Are competitiveness changes in the rest of the world (including climate regulation) a major driver of emissions in German industry? To understand the relative contributions of those different driving forces, we calculate counterfactuals where we allow all determinants of emissions in the model to follow their historical paths except one. By shutting off one by one each driver of German industrial emissions, we can assess the contribution of each driver to the actual emissions development. The result is shown in Figure 4.[27]

[27] We check the residuals from running the trust-region-reflective algorithm, and they are extremely small throughout. Setting all emission drivers to their historic values recreates the actual emission development.




(a)




(b)

Figure 4: Decomposition of actual German industrial emissions development where selective driving forces are held constant at their 2005 values while the other driving forces follow their historical paths

The red line shows the actual development in German industrial carbon emissions, according to the IEA, indexed to base year 2005.[28] All other lines show counterfactual emissions in which one emission driver is held constant at its 2005 value. If counterfactual emissions are larger than actual emissions, the development of the emission driver held constant has contributed to a decrease in emissions. If counterfactual emissions are smaller than the actual ones, the development of the emission driver held constant has contributed to an increase in emissions. The upper panel of Figure 4 focuses on the roles of the implicit carbon price developments.

Mimicking the decrease in climate policy stringency documented in the last subsection, the dashed black line in the figure shows that, except in early years, German industrial emissions would have been lower than they actually were had everything followed its historical path except German implicit carbon prices. By 2019, in the counterfactual, German industrial emissions would have been at 69% of their 2005 value, while actually, they were at about 79%. The German implicit carbon price development hence has contributed to an increase in industrial emissions.[29] The difference between the counterfactual with a constant implicit carbon price and actual emissions is not driven by strong differences in growth, but instead by the German sector composition. In the counterfactual with implicit carbon prices staying as high as in 2005, Germany would have grown less in the very emission intensive sectors (specifically the metals and pulp and paper sectors, where the elasticity of substitution is large, as well as the chemical sector). Conversely, labour would have been diverted toward less emission intensive sectors (like machinery, cars, or textiles). In that scenario, Germany would have reduced carbon emissions more.

Implicit carbon prices in the rest of the EU decreased as well, albeit less than in Germany. Given the single market in the EU, policy developments in other EU member states might have a significant impact on the German emissions development too. The

[28] The IEA emissions data differ from what we calculate with the more accurate German Manufacturing Census: According to the Census, industrial emissions have increased between 2005 and 2017, while they decreased slightly according to the IEA. Note however that qualitatively, the results of the decomposition are the same regardless of the emissions data we use. This is shown in Appendix Figure 16.

[29] The exact numbers of the counterfactual analysis are to be interpreted with caution and not taken as exact quantitative predictions due to the strong model assumptions. Among others, the (static) model abstracts from innovations in emission reducing technologies (i.e., firm-level productivity is constant over time), cannot capture effects down the supply chain, and assumes away adjustment costs.

purple line in the upper panel shows that this is indeed the case. Had every emissions driver followed its actual path except implicit carbon prices in the rest of the EU, German industrial emissions would have been lower. The actual development in EU implicit carbon prices led to an increase in German industrial emissions. It helped Germany grow in the emission intensive sectors of metal production and chemicals. The development in EU implicit carbon prices in isolation seems as important as the development in German implicit carbon prices in terms of magnitude. Our finding suggests that the differences in regulatory stringency within the EU documented in the last section might be significant for the emissions development. Arguably, given the small distance between EU countries and the high degree of market integration, even comparatively small regulatory differences might have large effects on production shifts, especially in sectors producing rather homogeneous products.

These are of course very stylized counterfactuals: Given the European scope of many climate policy instruments, neither German nor rest of the EU implicit carbon prices can meaningfully be held constant separately from developments in other EU member states. In the next subsection, we will focus on clearly disentangling the role of the difference in the developments in implicit carbon prices across Germany and the rest of the EU and show how German industrial emissions would have developed had the implicit carbon prices in the rest of the EU followed exactly the same path as the German one.

Emissions did not in fact decrease as much as they would have, had only German or only rest of the EU regulation stayed constant as in 2005. This is primarily due to the development of the different competitiveness drivers, as shown in panel (b). Specifically, our results imply that German competitiveness decreased over time. German production and hence German emissions would have increased without the loss of competitiveness (shown in the dotted black line of Figure 4). Part of German production however has been replaced by foreign production reducing the emissions occurring in Germany. Similarly, EU competitiveness generally decreased; in a counterfactual with only EU competitiveness held constant at 2005 values, German emissions would have decreased due to production shifts away from Germany (as visible in the solid black line). The impact of the competitiveness change in the rest of the world on German emissions is a lot weaker than the impact of changing competitiveness in the rest of the EU. In fact, running the model in a two-country world (Germany versus the rest of the world) results in counterfactual emissions under the foreign competitiveness scenario that are closer to those under the EU competitiveness scenario than to those under the ROW competitiveness scenario in a three-country world. Germany's trade linkages are strongest within the EU. In 2016, the share of German exports directed to the rest of the EU accounted for 58%, and the share of German imports originating from other EU countries for 67%. Importantly, in the emission intensive sectors, these shares tend to be higher, such as in pulp and paper (76% and 85%), coke and petroleum (72% and 71%), chemicals (61% and 76%), other non-metallic minerals (65% and 70%) and metals (67% and 76%). In that sense, what is going on in the rest of the world matters less to German emissions. Finally, the counterfactual on the role of the expenditure share development (solid purple line) suggests that worldwide, consumers shift spending toward emission intensive sectors.

## 5.2 Equating German and EU implicit carbon prices

To understand the importance of intra-European differences in implicit carbon prices, we run a counterfactual in which we equate German and EU carbon prices. Specifically, we assume EU regulation would have followed the same trajectory as the German one. We chose this counterfactual to understand the role of developments in regulatory stringency abroad for the domestic emissions of a single country. Setting the EU regulatory development equal to the German one, we can isolate the effect of relative policy stringency for Germany. In contrast, for the rest of the EU, the counterfactual conflates two effects, 1) the harmonisation of climate policies, and 2) a decrease in climate policy stringency.

Results are shown in Figure 5. Panel (a) shows the counterfactual emissions in Germany, panel (b) in the rest of the EU, assuming every emission driver followed its historical path except for EU regulation which instead takes on German values.[30]

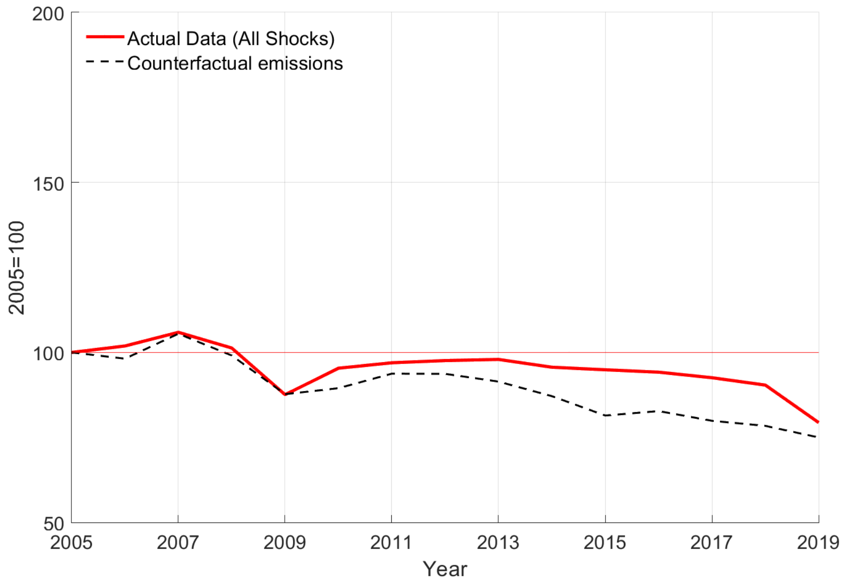
In the years prior to 2009, equating the implicit carbon price developments makes little difference suggesting that implicit carbon prices were very similar in the EU and Germany in these years. In later years however, German emissions would have been up to 16 percent lower compared to base year 2005 (in 2015 and 2017), had the EU

[30] Appendix Figures 14 and 15 show the according counterfactuals separately for the metals and paper sectors. Figure 17 shows the identical counterfactual analysis, however making use of data from the German Manufacturing Census for German industrial carbon emissions. Qualitatively, this does not change any of the above findings.

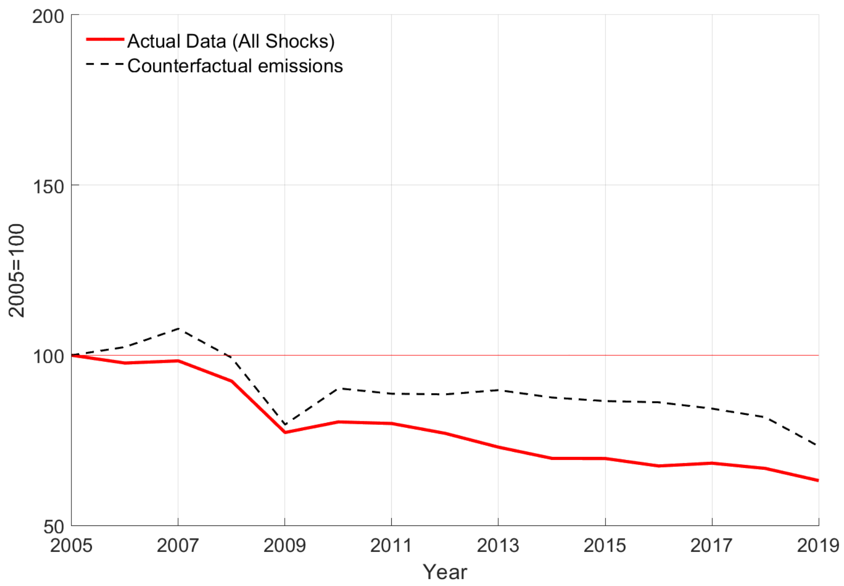
experienced the same change in carbon prices as Germany. In that scenario, the metals sector would have contracted substantially more in Germany than it actually did by 2019, driving much of the decline in emissions. The EU displays opposite patterns: Had the EU experienced the same decrease in implicit carbon prices as Germany, emissions would have been higher than they actually were. The relative difference between actual and counterfactual emissions is larger than for Germany, amounting to up to 29 percent (in 2016). At the EU-level, therefore, a harmonisation of the development of climate regulation would have led to larger emissions. EU emissions would have increased more than German emissions would have decreased. This is because German emission intensity in many sectors, including metals, was lower than the EU average in 2005.[31]

The main climate policy instrument at the EU level is the EU ETS. One advantage of an ETS is its allocative efficiency. This implies that emission reductions occur in places where these reductions are the cheapest. If the ETS was the only policy affecting emissions, our findings would be in line with the ETS leading to an efficient allocation of emissions in the EU. There are however overlapping policies affecting implicit carbon prices, as we argue in Section 4.3. Such overlapping policies can undermine not only the efficacy of an ETS (if the cap is not adjusted accordingly), but also its allocative efficiency. Germany has a history of compensating especially energy intensive industries for rising energy prices due to climate policy (e.g., electricity price compensation, exemptions from paying the full Renewable Energy Surcharge and grid charges) and has the financial means to implement such compensation. Against this background, it is not clear that the increase in German industrial emissions is efficient.

[31]Such an increase in emissions would of course also have had an impact on the ETS price which would likely have mitigated the increase in emissions.




(a)




(b)

Figure 5: Counterfactual with identical German and EU carbon price with all other emission drivers taking on their historical values (a) in Germany (top) (b) in the EU (bottom)

# 6 Conclusion

To reach net zero, carbon emissions across all sectors of the economy have to decline substantially. Emissions in German manufacturing are declining only slowly. In this paper, we use a quantitative equilibrium framework to learn about the underlying forces: Specifically, how did climate regulation in Germany and in other EU countries impact on the observed trends?

Applying the model framework, we show that the implicit price on carbon emissions in Germany declined strongly between 2005 and 2017, before rising again in the last years of the sample. This development in implicit carbon regulation mirrors the development of permit prices under the EU ETS. In addition to the EU ETS, fuel prices are shown to play a strong role for the implicit price on emissions. The implicit carbon price measure we extract from the model is not restricted to price policies, but also contains command and control measures. Our results indicate that price-based policies are strong determinants for the development of policy stringency however, and hence are key to reducing industrial emissions. Relative policy stringency is decisive especially in sectors where the elasticity of substitution is high.

While the EU's implicit carbon price also follows a declining trend, it is less pronounced than in Germany. We demonstrate that this difference plays a significant role for the German industrial emissions development: Had climate regulation in the EU followed exactly the same trend as in Germany, German emissions would have been up to 15 percentage points lower each year as compared to base year 2005 than they actually were. In sum, between 2005 and 2019, 264 million tonnes of carbon could have been "saved" in German industry by equating the development in regulation across the complete EU. This is approximately what German manufacturing emits in a single year. The reduction is mainly due to lower growth in the German metals sector had regulation trends been identical across the whole EU. The decline in German emissions would however have been counteracted by an even stronger increase in EU-level carbon emissions of 1,658 million tonnes.

These exact numerical results should be interpreted with caution, as the quantitative model comes with many simplifications. Specifically, as the model is static, we assume that firms cannot improve upon their productivity; that expectations do not matter; that labour supply is constant; and that there are no adjustment cost, i.e., labour freely moves across sectors. The important take-away from the paper however is that there are intra-European regulatory differences in terms of implicit carbon prices, and that they matter for the emissions of a single country. Our results imply that Germany has attracted carbon emissions through a relatively stronger decline in regulatory stringency than in other EU countries. As the model reformulation into changes does not allow us to uncover the implicit carbon prices in levels, it is not entirely clear whether Germany has become a pollution haven (i.e., has reduced carbon prices by more, starting from similar levels), or has just attempted to create a more level-playing field (i.e., has reduced carbon prices by more, starting from higher levels). Since German production in many sectors has been less carbon intensive than production in other world regions, the relocation of production within the EU may be efficient from a climate perspective. Germany may be becoming the EU carbon haven, but it is a comparatively clean one. Nevertheless, unilateral climate and energy policies within the EU can undermine the allocative efficiency of the ETS. A lack of (reliable) data on sector-level carbon emissions for the rest of the world however prohibits us from computing and comparing global carbon emissions under different scenarios. Therefore, it is not clear how global emissions would have developed, had German regulation followed a path similar to the rest of the EU.

While a lot of research has discussed carbon leakage and the countermeasure of a carbon border adjustment contrasting the EU and the rest of the world, our paper shows that the strong trade connection and spatial proximity of other EU countries make intra-EU production shifts in response to intra-EU regulatory differences highly likely – and maybe more so than production shifts to distant and not well integrated economies: We show that the improvements in the competitiveness (including climate regulation) of the rest of the world had a limited effect on the development of German carbon emissions. Hence, from a climate economic point of view, it would be helpful to work on harmonizing implicit carbon prices within the EU, rather than potentially engaging in a intra-European race to the bottom as we have seen it in response to the energy crisis after the Russian invasion of Ukraine in 2022.

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# Appendix

# 7 Model details

## 7.1 Price setting

Firms choose prices to maximise profits. Specifically, prices are set as constant markups over marginal cost:

$$p_{oi,s}(\varphi) = \frac{\sigma_s}{\sigma_s - 1} \frac{c_{o,s}\tau_{id,s}}{\varphi^{1-\alpha_s}} \tag{9}$$

In this equation, $c_{o,s}$ is a measure of cost:

$$c_{o,s} = \frac{(t_{o,s})^{\alpha_s}(w_{o,s})^{1-\alpha_s}}{(\alpha_s)^{\alpha_s}(1-\alpha_s)^{1-\alpha_s}} \tag{10}$$

## 7.2 Firm entry and cutoff productivity

Firms draw a productivity from a Pareto distribution at the expense of a fixed cost $f^e_{i,s}$, which is given by the following expression:

$$G(\varphi; b_{i,s}) = 1 - \frac{(b_{i,s})^{\theta_s}}{\varphi^{\theta_s}} \tag{11}$$

where $b_{i,s}$ is the location parameter. After observing their draw, firms decide whether or not to produce. At the cutoff productivity $\varphi^*_{id,s}$, they are indifferent between selling to market $d$ or not, as they make zero profit from doing so. The cutoff is given by:

$$\varphi^*_{id,s} = \left( \frac{\sigma_s}{\sigma_s - 1} \frac{c_{i,s}\tau_{id,s}}{P_{d,s}} \left( \frac{\sigma_s w_d f_{id,s}}{E_{d,s}} \right)^{\frac{1}{\sigma_s - 1}} \right)^{\frac{1}{1-\alpha_s}} \tag{12}$$

In this equation, $c_{i,s}$ is a measure of marginal cost (which depends on $i$'s taxes and wages), $P_{d,s}$ reflects the price index and $E_{d,s}$ country $d$'s expenditures in sector $s$.

## 7.3 Emissions technology and optimal abatement

Emissions by firm $\varphi$ in $o$ for sales in $i$ are proportional to production, and inversely proportional to abatement effort $a(\varphi)$:

$$z_{oi,s}(\varphi) = (1 - a(\varphi))^{\frac{1}{\alpha_s}} \varphi l_{oi,s}(\varphi) \tag{13}$$

$a(\varphi)$ constitutes the share of labour that is allocated to abatement instead of production. The effectiveness of abatement depends on the parameter $\alpha_s$, i.e., the pollution elasticity that captures the responsiveness of emissions with respect to abatement. Firms choose optimal abatement with the first order condition given by

$$1 - a = \left( \frac{w_o}{\varphi t_{o,s}} \frac{\alpha_s}{1 - \alpha_s} \right)^{\alpha_s} \tag{14}$$

## 7.4 The equilibrium conditions

In equilibrium, two conditions are satisfied:

*Labour market clearing:*

Labour market clearing ensures

$$L_i = L_i^e + L_i^p + L_i^t + L_i^m + L_i^{nx} \tag{15}$$

$L_i$ denotes a country's total labour supply. $L_i^e$ is the labour input used to pay the fixed entry cost, $L_i^p$ the input for production (including emissions abatement), $L_i^t$ is used to pay the carbon tax, $L_i^m$ for market entry cost, and $L_i^{nx}$ for net exports.

*Free entry:*

The free entry condition requires that the fixed cost of drawing a productivity are equal to the expected profits of doing so:

$$w_i f_{i,s}^e = \left(1 - G\left[\varphi_{ii,s}^*\right]\right) E\left[\pi|\varphi > \varphi_{ii,s}^*\right] \tag{16}$$

If the model is rewritten in changes following the hat-algebra by Dekle *et al.* (2008), these equilibrium conditions can be expressed in the following way:

$$1 = \psi_o \left( \frac{\sum_s \hat{M}_{o,s} \hat{R}_{o,s} \frac{(\sigma_s - 1)(\theta_s - \alpha_s + 1)}{\sigma_s \theta_s} + \frac{1}{\hat{w}_o} \eta'_{os}}{\sum_s R_{o,s} \frac{(\sigma_s - 1)(\theta_s - \alpha_s + 1)}{\sigma_s \theta_s} + \eta_{o,s}} \right) \tag{17}$$

$$\hat{w}_o = \sum_d \frac{\zeta_{od,s} \left(\frac{\hat{w}_o}{\hat{b}_{o,s}}\right)^{-\theta_s} \left(\hat{\tau}_{od,s}\right)^{-\frac{\theta_s}{1-\alpha_s}} \left(\hat{f}_{od,s}\right)^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}} \left(\hat{t}_{o,s}\right)^{-\frac{\alpha_s \theta_s}{1-\alpha_s}}}{\sum_i \lambda_{id,s} \hat{M}_{i,s}^e \left(\frac{\hat{w}_o}{\hat{b}_{o,s}}\right)^{-\theta_s} \left(\hat{\tau}_{od,s}\right)^{-\frac{\theta_s}{1-\alpha_s}} \left(\hat{f}_{od,s}\right)^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}} \left(\hat{t}_{o,s}\right)^{-\frac{\alpha_s \theta_s}{1-\alpha_s}}} \hat{\beta}_{d,s} \frac{R'_d - NX'_d}{R_d - NX_d} \tag{18}$$

Hats denote the proportional change in a variable in a counterfactual scenario (counterfactual values are denoted by primes) relative to the base value. In these equations, $\psi_o$ and $\eta_o$ constitute parameter combinations.[32] $M_{i,s}$ represents the mass of entering firms in country $i$ and sector $s$, $R_{i,s}$ total revenues and $NX_i$ net exports. $\zeta_{id,s}$ and $\lambda_{id,s}$ denote export and import shares, respectively, i.e. the value of country $i$'s production (expenditure) that is exported (imported) to (from) country $d$ in sector $s$.

## 7.5 The measurement of competitiveness drivers

The following equations show how the competitiveness drivers described in Section 2 are measured. Measurement follows reformulation of the model. Details on the procedure can be found in Shapiro and Walker (2018).

*Competitiveness driver net of regulation:*

$$\begin{aligned} \hat{\Gamma}_{od,s}^* &\equiv (1/\hat{b}_{o,s})^{-\theta_s} (\hat{\tau}_{od,s})^{-\frac{\theta_s}{1-\alpha_s}} (\hat{f}_{od,s})^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}} \\ &= (\hat{t}_{o,s})^{\frac{\alpha_s \theta_s}{1-\alpha_s}} \frac{\hat{\lambda}_{od,s}}{\hat{M}_{o,s}^e \hat{w}_o^{-\theta_s}} (\hat{P}_{d,s})^{\frac{\theta_s}{1-\alpha_s}} \left( \frac{\hat{\beta}_{d,s}}{\hat{w}_d} \frac{R'_d - N\hat{X}_d NX_d}{R_d - NX_d} \right)^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}} \end{aligned} \tag{21}$$

[32]Specifically, they are given by the following equations:

$$\psi_o \equiv \left[1 - \sum_s \frac{\theta_s - (\sigma_s - 1)(1 - \alpha_s)}{\sigma_s \theta_s} \beta_{o,s}\right] / \left[1 - \sum_s \frac{\theta_s - (\sigma_s - 1)(1 - \alpha_s)}{\sigma_s \theta_s} \beta'_{o,s}\right] \tag{19}$$

$$\eta_{o,s} \equiv \sum_s \left[ -\frac{\theta_s - (\sigma_s - 1)(1 - \alpha_s) - \sigma_s \theta_s}{\sigma_s \theta_s} \beta_{o,s} NX_o - NX_{o,s} \frac{(\sigma_s - 1)(\theta_s - \alpha_s + 1)}{\sigma_s \theta_s} \right] \tag{20}$$

with $o \neq ROW$

*Competitiveness driver including regulation:*

$$\hat{\Gamma}^*_{do,s} \equiv (1/\hat{b}_{d,s})^{-\theta_s} (\hat{\tau}_{do,s})^{-\frac{\theta_s}{1-\alpha_s}} (\hat{f}_{do,s})^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}} (\hat{t}_{d,s})^{-\frac{\alpha_s\theta_s}{1-\alpha_s}}$$
$$= \frac{\hat{\lambda}_{od,s}}{\hat{M}^e_{o,s}\hat{w}_o^{-\theta_s}} (\hat{P}_{d,s})^{\frac{\theta_s}{1-\alpha_s}} \left( \frac{\hat{\beta}_{d,s}}{\hat{w}_d} \frac{R'_d - \hat{NX}_d NX_d}{R_d - NX_d} \right)^{1-\frac{\theta_s}{(\sigma_s-1)(1-\alpha_s)}} \quad (22)$$

with $o = ROW$

While destination price index data are generally not available, counterfactuals can be analysed without measuring $\hat{P}_{d,s}$. That is because in the second equilibrium condition (18), they cancel out in numerator and denominator. Thus, counterfactual emissions calculated using competitiveness measures omitting price indices are equal to counterfactual emissions retrieved from plugging in accurate measures of competitiveness drivers that incorporate price indices. At the same time, however, historical measures for domestic and foreign competitiveness are not informative as they omit the price index information and we refrain from interpreting them.

# 8 Data details

## 8.1 Concordance tables ISIC Rev. 3 – NACE 2

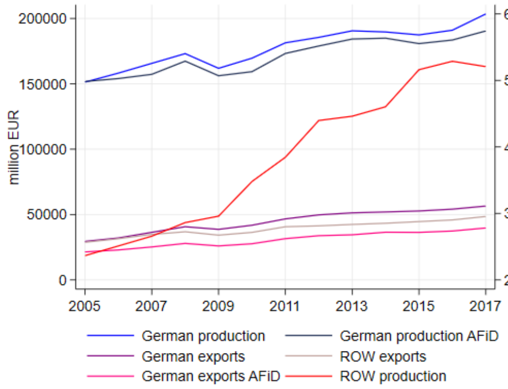
Table 4: Concordance ISIC Rev. 3 – NACE 2

Taken from the INDSTAT 2 metadata

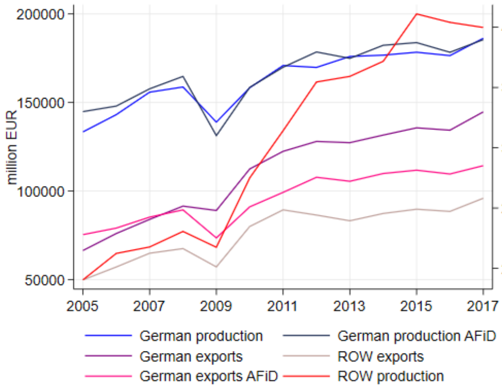
| **ISIC Rev. 3 Code** | **Description** | **NACE 2 Code** |
|---|---|---|
| 15 | Food and beverages | 10 and 11 |
| 16 | Tobacco products | 12 |
| 17 | Textiles | 13 |
| 18 | Wearing apparel, fur | 14 |
| 19 | Leather, leather products and footwear | 15 |
| 20 | Wood products (no furniture) | 16 |
| 21 | Paper and paper products | 17 |
| 22 | Printing and publishing | 18 |
| 23 | Coke, refined petroleum products, nuclear fuel | 19 |
| 24 | Chemicals and chemical products | 20 and 21 |
| 25 | Rubber and plastic products | 22 |
| 26 | Non-metallic mineral products | 23 |
| 27 | Basic metals | 24 |
| 28 | Fabricated metal products | 25 |
| 29 | Machinery and equipment | 28 and 33 |
| 30 | Office, accounting and computing machinery | 26 |
| 31 | Electrical machinery and apparatus | 27 |
| 32 | Radio, television and communication equipment | 26 |
| 33 | Medical, precision and optimal instruments | 26 |
| 34 | Motor vehicles, trailers, semi-trailers | 29 |
| 35 | Other transport equipment | 30 |
| 36 | Furniture; manufacturing n.e.c. | 31 and 32 |

## 8.2 Comparing German export and production data from different data sources

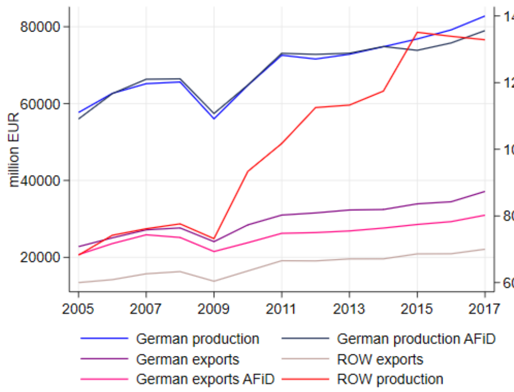
The following graphs compare production (dark blue, dark red) and export (green, yellow) from aggregate data sources (UNIDO and Eurostat) versus the German Manufacturing Census (AFiD). The comparison is exemplary depicted for sectors 10/11, 20/21, 22 and 29, but generally the patterns hold across all sectors. As can be seen, numbers are generally similar and follow similar trends, even though levels are not always identical. Differences between the data sources can be explained by inaccurate sector recodings, different exact measurements as well as the manufacturing Census not covering very small plants (below 20 employees).



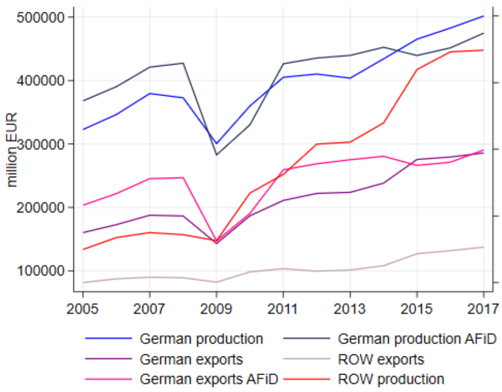

(a)




(b)




(c)




(d)

Figure 6: production and trade data for Germany and the rest of the world from different data sources for sectors (a) 10, 11 and 12 (food, beverages and tobacco) (b) 20 and 21 (chemicals and pharmaceuticals) (c) 22 (rubber and plastics) (d) 29–32 (vehicles, other transport, other)

## 8.3 Comparing IEA emissions data to emissions computed with the German manufacturing Census

We take sector-level emissions from the IEA database “Energy Efficiency Indicators”. The IEA computes emissions by multiplying the energy consumption with an emission factor, implied by the fuel mix from the IEA energy balances in combination with default fuel-specific emission factors. This is the same approach we follow for calculating emissions from the German Manufacturing Census. The IEA however assigns no emissions to the use of biofuels. Generally, relatively detailed data are available for the industrial sector for IEA countries. Data are collected from a variety of sources, including administrative data, and surveys. For Germany, e.g., energy use of a given sector is taken from the Fraunhofer Institute for Systems and Innovation Research’s FORECAST-Industry model. For other countries, such as Belgium, Italy or Spain, administrative data are used. For more information, the reader is referred to the database documentation and the accompanying document “Energy Efficiency Indicators: Fundamentals on Statistics”.

Table 5 shows the average and median percentage deviation between German carbon emissions from IEA and manufacturing Census over the years 2005 to 2017 (for which both data sources are available). Percentage deviations are calculated by subtracting the Census emissions from the IEA emissions and dividing by the Census values.

As can be seen, in most sectors, the deviations are below 5%. Generally, the emissions data from the IEA are a bit too small. However, there are larger deviations in sectors 19 (coke and petroleum) and 24 (metal production); in the former sector, IEA emissions are substantially larger, in the latter tremendously smaller. The coke and petroleum sector is a rather small sector (in terms of the number of firms) and therefore information on it tends to be less accurate than in other sectors. Metal production in contrast involves energy consumption in transformation for coke ovens and blast furnaces, where allocation of emissions might be challenging.

Figure 7 shows the aggregate development of carbon emissions according to both data sources over time. As can be seen, while emission paths generally are similar, over the last years of the sample, emissions diverge: According to the IEA, emissions by 2017 were lower than in 2005, while (the more accurate) manufacturing Census shows an increase in emissions.

Table 5: Percentage deviation between emissions from IEA and German manufacturing Census across sectors

| NACE 2 Code | Average deviation | Median deviation |
|---|---|---|
| 10 to 12 | -0.033 | -0.039 |
| 13 to 15 | -0.055 | -0.055 |
| 16 | -0.032 | -0.031 |
| 17 and 18 | -0.011 | -0.017 |
| 19 | 0.129 | 0.142 |
| 20 and 21 | -0.060 | -0.095 |
| 22 | -0.038 | -0.039 |
| 23 | -0.074 | -0.080 |
| 24 | -0.318 | -0.345 |
| 25 to 28, 33 | -0.045 | -0.037 |
| 29 to 32 | -0.051 | -0.055 |

Our analysis does not rely on emissions data in levels, but in changes as compared to our base year. As long as sector-level emission paths develop similar in the different data sets, the (partly substantial) differences across data sets do not matter. For robustness, however, we also run the analysis using the emissions from the manufacturing census for Germany which limits the analysis window to the time period between 2005 and 2017. Qualitatively, the results are unchanged, as reported in the Appendix.


Figure 7: Aggregate emissions development in German manufacturing according to IEA and Manufacturing Census

## 8.4 Correction of trade data to account for re-exports

Re-exports are a well-known challenge encountered in combining production and trade data. Intuitively, the problem occurs because exports not produced in the exporting country are counted as exports, but not as production – which means that exports of a given good can exceed actual production. The issue becomes larger the smaller the unit analysed: For a single country, all exports which have been imported previously constitute re-exports; if country groups are analysed, only the exports that have been imported from third countries outside of the country group itself, and additionally are exported to third countries are re-exports. Everything that would represent re-exports from the perspective of a single country, but stays within the country group, constitutes intra-group trade.

We use data from Eurostat input-output tables to correct for re-exports, specifically from the import use matrix. For Germany and the EU28 (including Germany), we compute the share of imports that are exported to the EU and to the rest of the world, respectively. For Germany, in 2016, the share of imports exported again gets as large as 43% for the pharmaceuticals sector (NACE 21). With about 3%, the share is smallest in the coke and petroleum sector (NACE 19). For the EU28, numbers are generally lower, due to intra-group trade not being counted as re-exports. Note that for the rest of the EU in our model, we use the values of the EU28, that include Germany (which it strictly speaking should not, in our context). However, the error is likely to be small. Computing shares for the EU without Germany from country-level input-output tables would require knowledge to where exactly imported goods are exported to, in order to accurately distinguish within-group versus out-of-group exports. These data are not available to us.

As we treat our model as a three-country world, for Germany, we calculate separate shares (of imports that are exported again) for the rest of the world and the EU. That is necessary because shares can differ widely: In the car industry (NACE 29), e.g., only about 5% of total imports are re-exported to other EU countries, but 24% to countries outside of the EU.

We multiply the calculated re-export shares of imports with total imports to obtain a measure of total re-exports that differ by country, sector and year. Then we subtract these re-exports from both the import and export numbers such that trade patterns of each country only reflect trade in own production. Note that we do not need any input-output table for the rest of the world, as trade is symmetric (i.e., German imports from ROW are equal to ROW exports to Germany). Therefore, ROW trade patterns are automatically adjusted by correcting EU and German trade flows.

## 8.5 Details on parameter estimation

We estimate the Pareto shape parameter $\theta_s$ by regressing log firm sales on log firm's sales rank, as described in the main text. The shape parameter is recovered by combining the estimated coefficient, shown in column (1) of Table 6, with the elasticity of substitution.

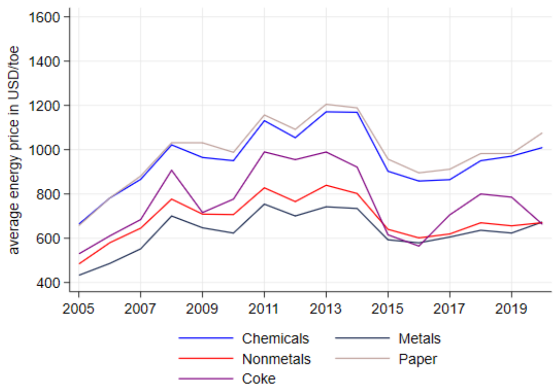
Column (2) of Table 6 reports the estimated multiplicative markups that are needed to back out the elasticity of substitution $\sigma_s$. Column (3) reports the estimated energy output elasticities (i.e., energy cost shares from revenues), and column (4) contains the elasticity of emissions to energy input, retrieved from log-log regressions. All numbers are for 2005.

Table 6: Intermediate results for the parameter estimation

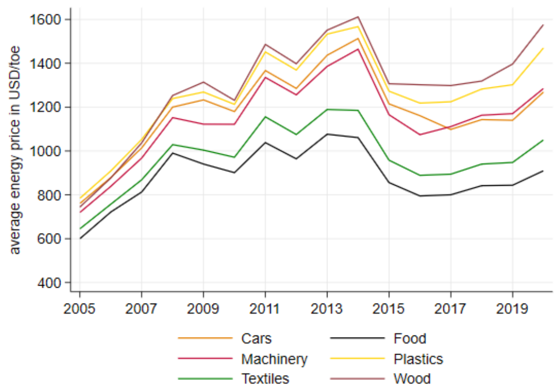
| **NACE 2 Code** | **Coefficient estimate for $\theta_s$** | **Markups** | **Energy output elasticity** | **Emissions elasticity** |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| 10 to 12 | -1.391 | 1.695 | 0.016 | 0.974 |
| 13 to 15 | -2.065 | 1.316 | 0.018 | 1.002 |
| 16 | -1.708 | 1.316 | 0.031 | 0.873 |
| 17 and 18 | -1.825 | 1.177 | 0.059 | 0.962 |
| 19 | -1.038 | 2.326 | 0.007 | 1.001 |
| 20 and 21 | -1.239 | 1.539 | 0.034 | 0.993 |
| 22 | -1.652 | 1.333 | 0.022 | 1.012 |
| 23 | -1.924 | 1.389 | 0.065 | 0.946 |
| 24 | -1.277 | 1.235 | 0.061 | 0.993 |
| 25 to 28, 33 | -1.363 | 1.205 | 0.010 | 1.011 |
| 29 to 32 | -0.936 | 1.205 | 0.008 | 1.001 |

## 8.6 Energy price data

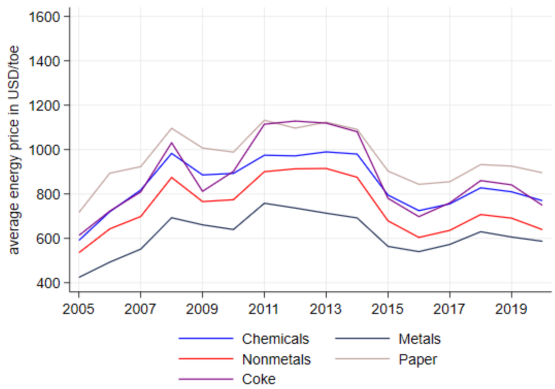
We take energy price data from the IEA (2022b). Time-varying fuel prices for industry are weighted by a sector's fuel mix in each year to compute one average energy price. Country-level prices are aggregated to the EU-level by taking a weighted average of prices, where weights are given by the country's energy consumption relative to total EU energy consumption in a given sector. Missings (especially for coal prices) are filled in by averages of other reporting countries in a given year. Figure 8 shows the development of the computed average energy prices for different sectors in Germany and the rest of the EU, respectively.



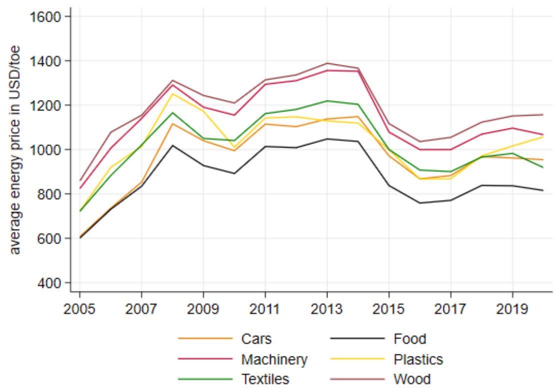

(a)




(b)




(c)




(d)

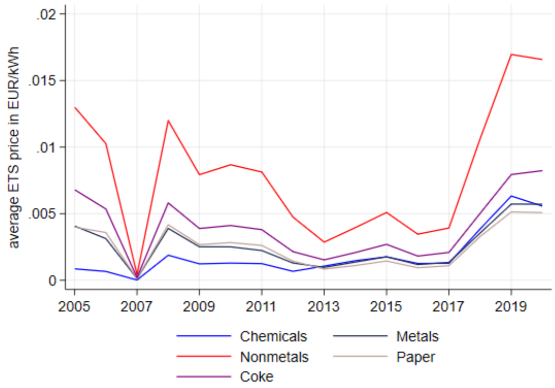
Figure 8: average energy prices in different sectors in USD/toe (a) in Germany in ETS sectors (b) in Germany in non-ETS sectors (c) in the rest of the EU in ETS sectors (d) in the rest of the EU in non-ETS sectors

## 8.7 ETS price data

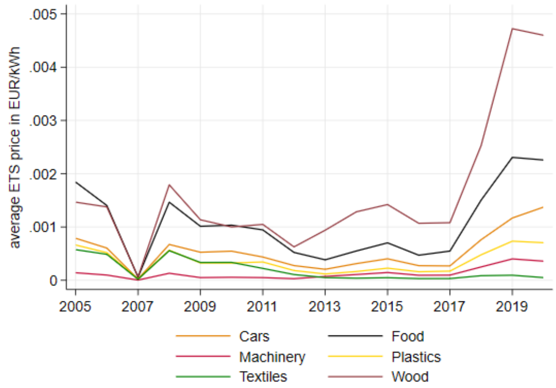
We calculate the permit prices under the EU ETS different sector/country/year combinations had to pay, taking into account the sector's coverage under the EU ETS, as well as sector-level fuel mixes.

Average annual permit prices under the EU ETS are taken from Statista. These permit prices are multiplied with a sector-country-year specific emission intensity. We obtain this emission intensity by dividing verified emissions under the EU ETS from the EU's transaction log by the sector's fossil energy use in a given country and year (taken from the IEA 2022a). This emission intensity reflects both the sector's fuel mix (i.e., verified emissions per kWh of energy use are higher with a dirtier fuel mix) and the sector's coverage under the EU ETS (i.e., sectors in which many installations are subject to the EU ETS have higher verified emissions). Note that generally, a sector's average permit price calculated this way is too high, as verified emissions also contain process emissions. Unfortunately, however, the EUTL data does not allow us to separate process from combustion emissions. The error however is likely to be small, as we only make use of the development in average ETS prices, not their levels.

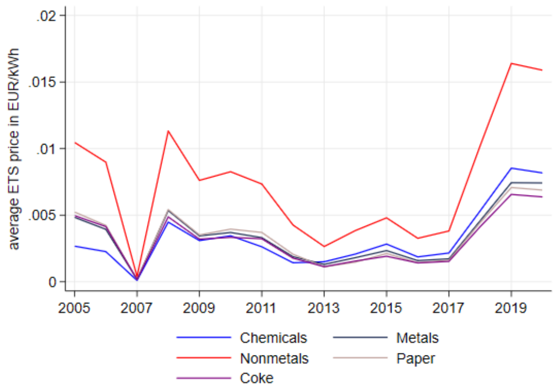
The development of the resulting permit prices is shown in Figure 9. As can be seen, prices across sectors generally follow the same trend, namely the trend of permit prices. Still, there is substantial variation as some sectors (such as textiles or machinery) are barely directly regulated under the EU ETS.



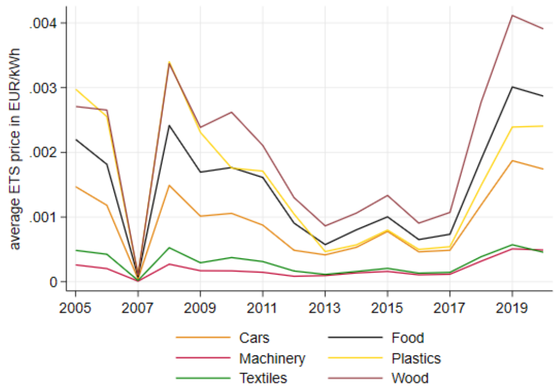

(a)




(b)




(c)



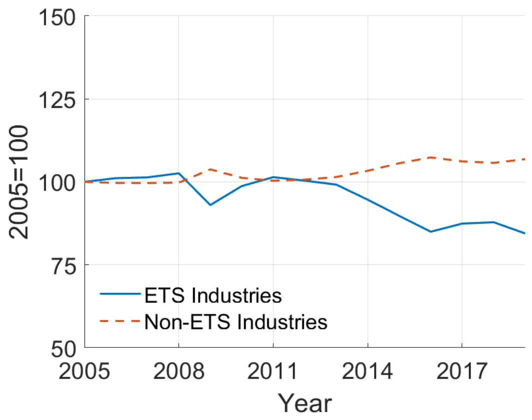

(d)

Figure 9: average permit prices in different sectors in EUR/kWh (a) in Germany in ETS sectors (b) in Germany in non-ETS sectors (c) in the rest of the EU in ETS sectors (d) in the rest of the EU in non-ETS sectors

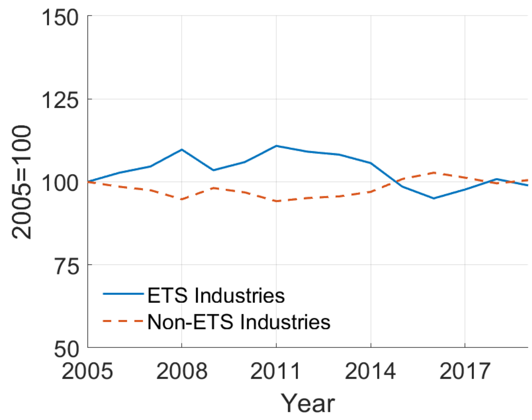
# 9 Additional model results

## 9.1 Historical developments of emission drivers and the accompanying development of endogenous variables

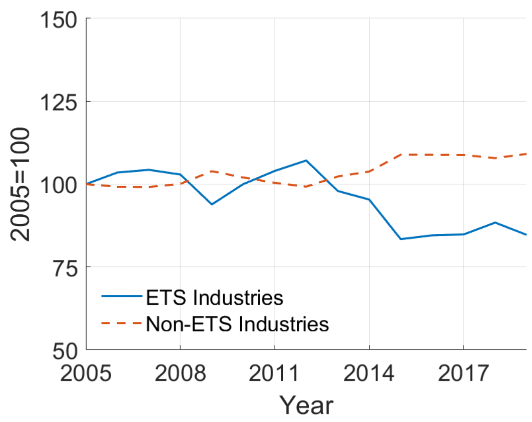
The following graphs show the historical development of the domestic and foreign expenditure share drivers, as well as the development of endogenous variables (firm entries, wages) in the different countries. Historical competitiveness drivers are not shown as they are not informative due to the omission of price index data. Note that real wages are not sector-specific and hence, for real wages, results are not split across ETS- and non-ETS-sectors. For all other depicted variables, the results are simple arithmetic averages across sectors.




(a)




(b)




(c)

Figure 10: Development of the expenditure share driver (a) in Germany (b) for the rest of the world (c) for the rest of the EU

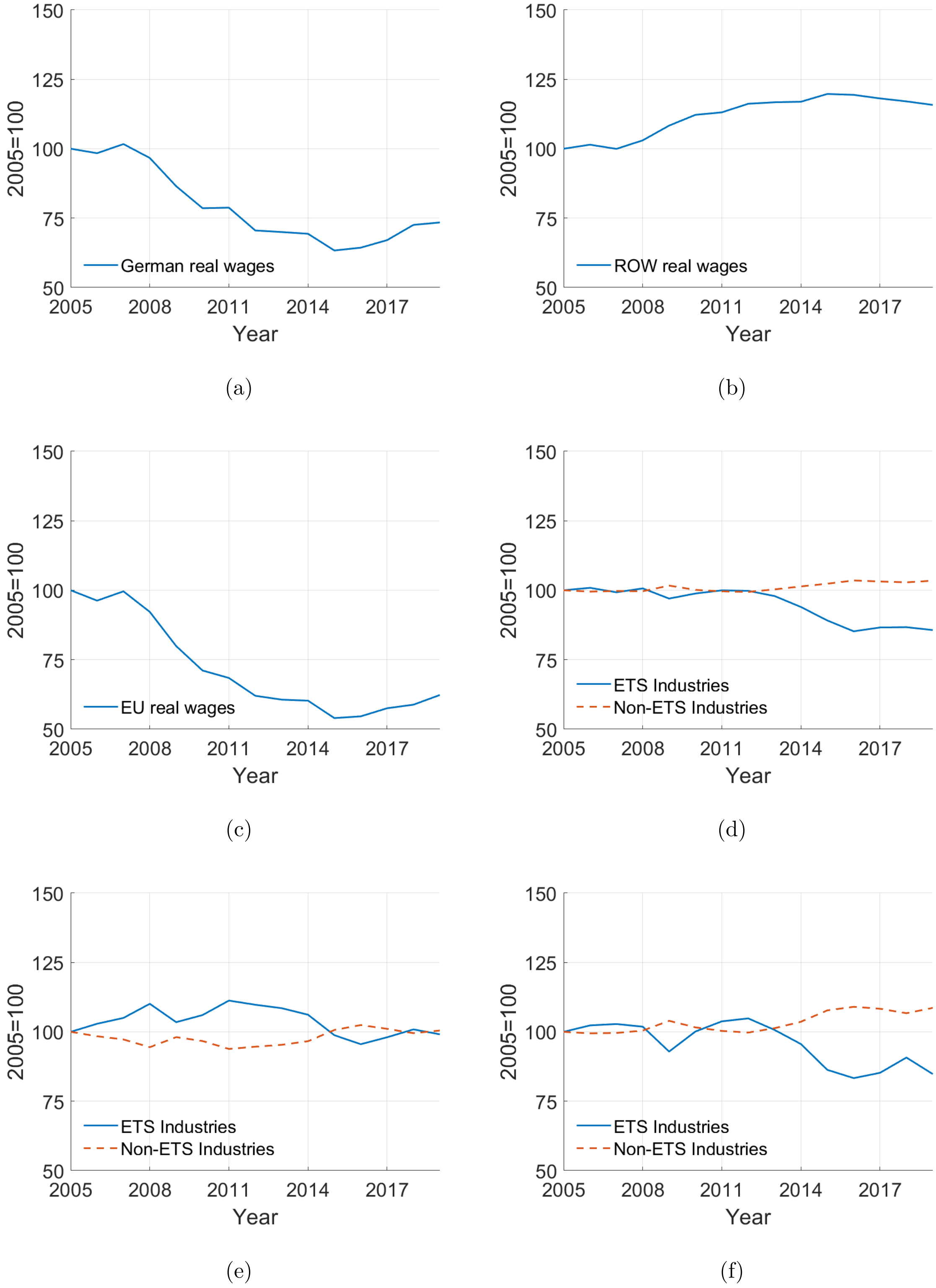


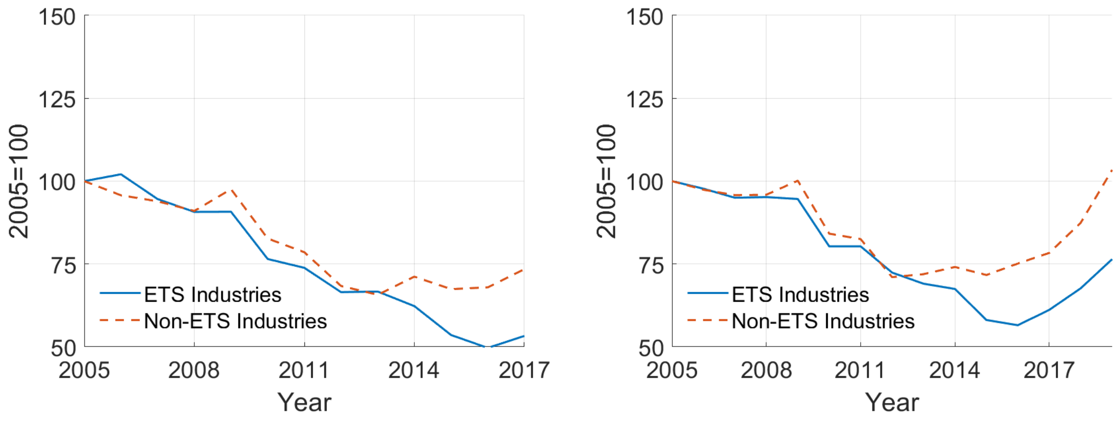

Figure 11: Development of endogenous variables when all emission drivers take on historical values: (a) German real wages (b) foreign real wages (c) EU real wages (d) German firm entries (e) foreign firm entries (f) EU firm entries

### Historical regulation driver by sector

Table 7: Historical regulation driver by sector

| NACE 2 Code | region | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 to 12 | DE | 1 | 0.94 | 0.92 | 0.96 | 1.01 | 0.85 | 0.79 | 0.71 | 0.72 | 0.70 | 0.64 | 0.64 | 0.69 | 0.72 | 0.84 |
| | EU | 1 | 0.99 | 1.00 | 1.02 | 1.16 | 0.95 | 0.91 | 0.85 | 0.91 | 0.91 | 0.80 | 0.81 | 0.84 | 0.68 | 0.96 |
| 13 to 15 | DE | 1 | 1.03 | 0.96 | 0.96 | 1.06 | 0.87 | 0.83 | 0.70 | 0.77 | 0.84 | 0.72 | 0.75 | 0.79 | 0.84 | 1.02 |
| | EU | 1 | 1.00 | 1.07 | 1.07 | 1.18 | 1.06 | 1.05 | 0.94 | 0.99 | 1.10 | 1.04 | 1.08 | 1.08 | 1.16 | 1.28 |
| 16 | DE | 1 | 0.96 | 0.93 | 0.84 | 0.89 | 0.77 | 0.74 | 0.66 | 0.71 | 0.74 | 0.69 | 0.67 | 0.66 | 0.75 | 0.97 |
| | EU | 1 | 0.93 | 0.99 | 0.96 | 0.96 | 0.81 | 0.76 | 0.69 | 0.71 | 0.80 | 0.73 | 0.71 | 0.70 | 0.78 | 0.89 |
| 17 and 18 | DE | 1 | 0.99 | 0.91 | 0.66 | 0.69 | 0.58 | 0.55 | 0.46 | 0.45 | 0.44 | 0.41 | 0.42 | 0.45 | 0.50 | 0.59 |
| | EU | 1 | 0.92 | 0.95 | 0.89 | 0.66 | 0.56 | 0.55 | 0.49 | 0.49 | 0.50 | 0.50 | 0.51 | 0.51 | 0.58 | 0.63 |
| 19 | DE | 1 | 0.97 | 0.81 | 0.96 | 0.84 | 0.77 | 0.79 | 0.80 | 0.69 | 0.66 | 0.51 | 0.45 | 0.48 | 0.49 | 0.54 |
| | EU | 1 | 0.89 | 0.95 | 0.92 | 0.81 | 0.84 | 0.97 | 1.03 | 0.99 | 0.88 | 0.52 | 0.57 | 0.57 | 0.59 | 0.73 |
| 20 and 21 | DE | 1 | 0.95 | 0.89 | 0.90 | 0.98 | 0.81 | 0.79 | 0.66 | 0.68 | 0.67 | 0.60 | 0.61 | 0.64 | 0.75 | 0.87 |
| | EU | 1 | 1.02 | 1.03 | 0.99 | 1.03 | 0.92 | 0.82 | 0.77 | 0.78 | 0.81 | 0.71 | 0.70 | 0.77 | 0.88 | 0.82 |
| 22 | DE | 1 | 0.93 | 0.88 | 0.88 | 0.94 | 0.77 | 0.80 | 0.69 | 0.69 | 0.71 | 0.67 | 0.68 | 0.74 | 0.86 | 1.01 |
| | EU | 1 | 0.91 | 0.93 | 0.91 | 0.92 | 0.73 | 0.74 | 0.65 | 0.58 | 0.61 | 0.61 | 0.60 | 0.65 | 0.71 | 0.79 |
| 23 | DE | 1 | 0.96 | 0.90 | 0.93 | 1.05 | 0.84 | 0.83 | 0.76 | 0.78 | 0.79 | 0.70 | 0.72 | 0.74 | 0.79 | 0.89 |
| | EU | 1 | 1.03 | 1.04 | 1.01 | 1.13 | 0.91 | 0.85 | 0.77 | 0.79 | 0.81 | 0.74 | 0.75 | 0.81 | 0.86 | 0.96 |
| 24 | DE | 1 | 1.03 | 1.21 | 1.19 | 1.12 | 0.93 | 0.98 | 0.87 | 0.80 | 0.78 | 0.68 | 0.65 | 0.75 | 0.82 | 0.89 |
| | EU | 1 | 1.13 | 1.20 | 1.22 | 1.11 | 1.04 | 1.04 | 0.90 | 0.88 | 0.91 | 0.82 | 0.80 | 0.88 | 1.01 | 1.03 |
| 25 to 28, 33 | DE | 1 | 0.98 | 0.97 | 0.94 | 0.96 | 0.81 | 0.79 | 0.67 | 0.69 | 0.69 | 0.70 | 0.77 | 0.77 | 0.88 | 1.06 |
| | EU | 1 | 0.99 | 1.04 | 1.06 | 1.09 | 0.90 | 0.87 | 0.83 | 0.85 | 0.92 | 0.83 | 0.85 | 0.87 | 0.95 | 1.05 |
| 29 to 32 | DE | 1 | 0.98 | 1.00 | 1.04 | 1.09 | 0.92 | 0.94 | 0.81 | 0.76 | 0.85 | 0.84 | 0.85 | 0.92 | 1.03 | 1.18 |
| | EU | 1 | 0.94 | 0.94 | 0.89 | 0.95 | 0.77 | 0.73 | 0.66 | 0.67 | 0.75 | 0.76 | 0.85 | 0.86 | 0.91 | 1.02 |

## 9.2 Historical German regulation driver using different emissions data




(a) (b)

Figure 12: Development of implicit price on carbon emissions in Germany (a) using data from the German Manufacturing Census (b) using data from the IEA (right) on German industrial carbon emissions

## 9.3 Decomposition of emissions drivers with two versus three world regions

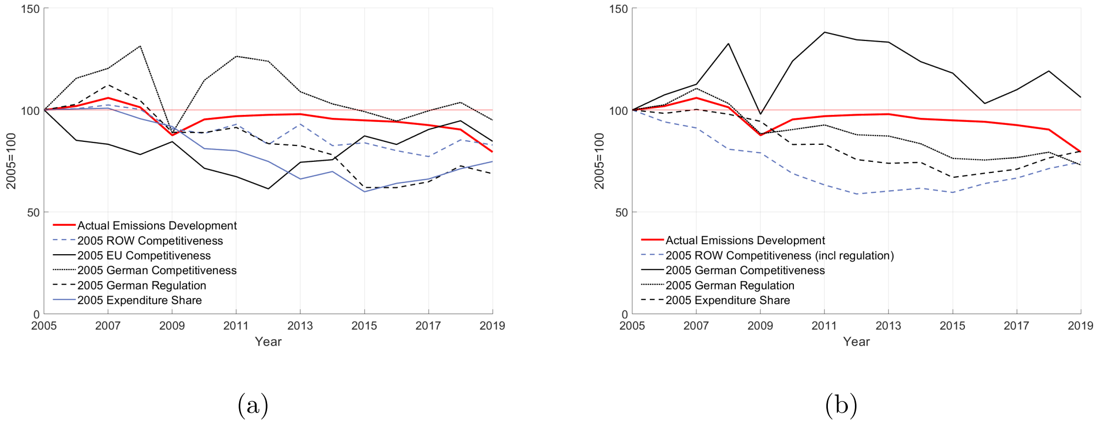
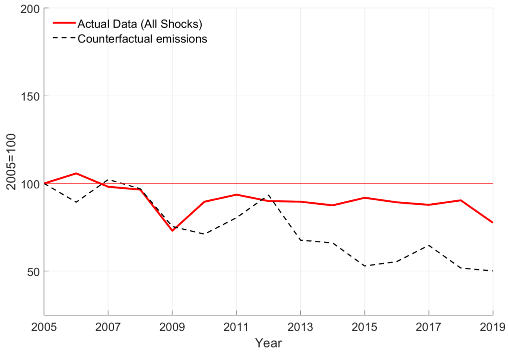
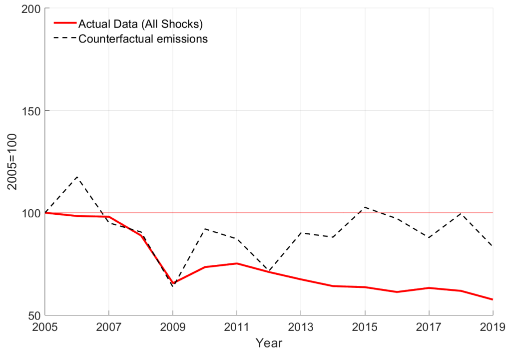



Figure 13: Decomposition of actual German industrial emissions development (a) with three world regions (left) (b) with two world regions (right)

## 9.4 Counterfactual emissions with identical German and EU regulation developments for specific sectors

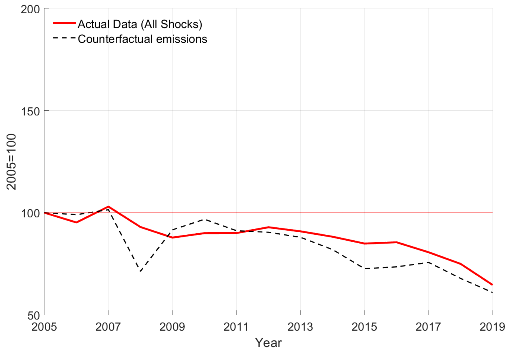



(a)

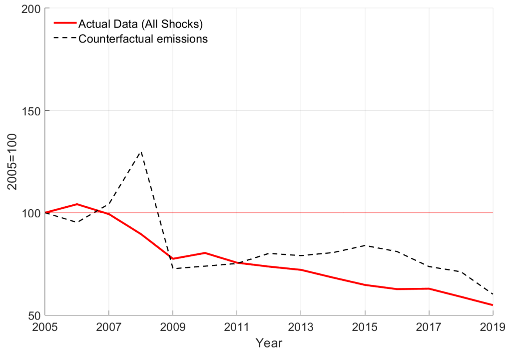



(b)

Figure 14: Counterfactual in the metals sector with identical German and EU carbon price development with all other emission drivers taking on their historical values (a) in Germany (left) (b) in the EU (right)



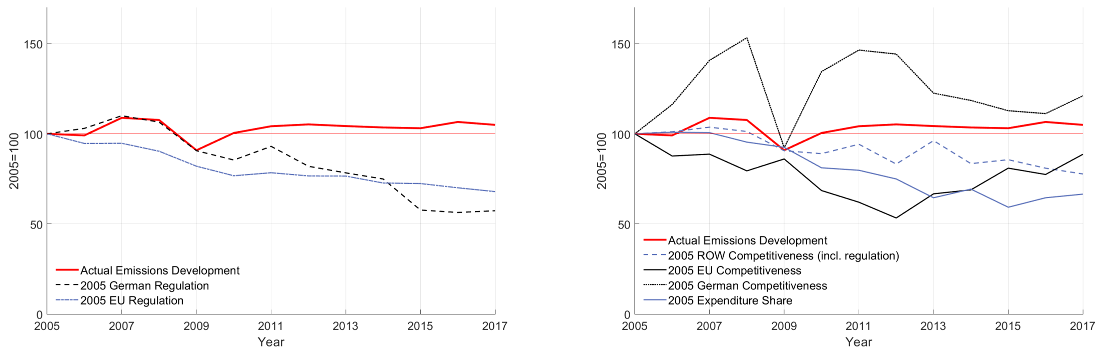

(a)




(b)

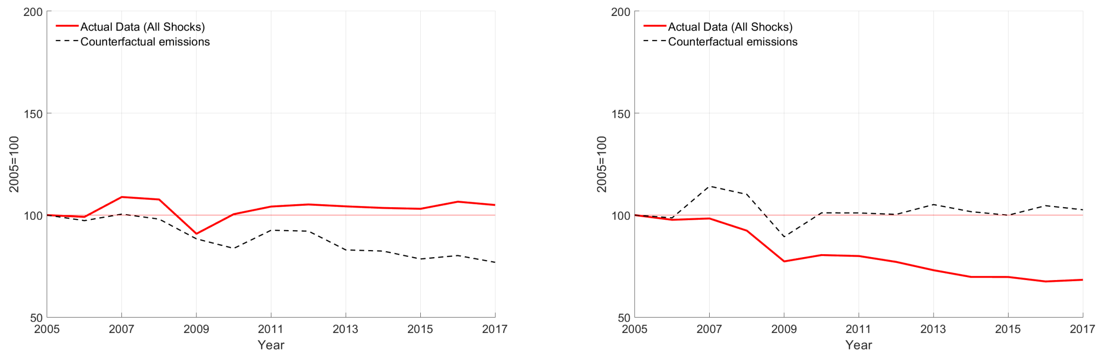
Figure 15: Counterfactual in the pulp, paper and publishing sector with identical German and EU carbon price development with all other emission drivers taking on their historical values (a) in Germany (left) (b) in the EU (right)

### 9.5 Counterfactual analysis equating German and EU regulation, using emissions data from the German Manufacturing Census




(a) (b)

Figure 16: Decomposition of actual German industrial emissions development where selective driving forces are held constant at their 2005 values while the other driving forces follow their historical paths using the German Manufacturing Census




(a) (b)

Figure 17: Counterfactual emissions with identical German and EU carbon price developments with all other emission drivers taking on their historical values (a) in Germany (left) (b) in the EU (right)

## 9.6 Development of emission intensities of production in different sectors

The Table below shows the emission intensities of production in Germany and the rest of the EU over time. Emission intensities are calculated by simply dividing IEA sector-level emissions by the (non-deflated) UNIDO production in EUR. Values are expressed as grams of CO2 per EUR of output.

Table 8: Emission intensities of production

| NACE 2 Code | region | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 to 12, | DE | 123.9 | 118.8 | 117.1 | 107.6 | 111.2 | 105.9 | 101.6 | 102.2 | 99.6 | 99.0 | 98.1 | 98.6 | 89.9 | 89.2 | 76.0 |
| Food | EU | 128.8 | 118.4 | 111.8 | 104.8 | 101.1 | 98.6 | 91.8 | 88.3 | 82.3 | 79.1 | 81.2 | 80.3 | 76.5 | 97.9 | 69.2 |
| 13 to 15, | DE | 126.1 | 111.3 | 114.4 | 108.6 | 107.8 | 105.3 | 98.5 | 104.1 | 94.8 | 84.3 | 88.7 | 85.2 | 79.6 | 77.9 | 64.3 |
| Textiles | EU | 143.5 | 130.0 | 116.4 | 111.7 | 110.2 | 97.9 | 88.5 | 89.1 | 84.4 | 73.0 | 69.6 | 67.5 | 66.3 | 64.4 | 58.1 |
| 16, Wood | DE | 168.4 | 159.2 | 157.9 | 166.6 | 171.6 | 159.0 | 148.3 | 149.4 | 137.1 | 127.9 | 124.3 | 126.8 | 128.0 | 116.2 | 90.2 |
| | EU | 151.9 | 147.5 | 133.0 | 131.7 | 143.6 | 135.2 | 129.1 | 127.3 | 123.8 | 107.3 | 105.5 | 108.2 | 108.5 | 100.8 | 88.1 |
| 17 and 18, | DE | 298.5 | 274.0 | 284.2 | 376.9 | 391.6 | 369.9 | 353.5 | 378.6 | 381.4 | 378.0 | 366.2 | 360.1 | 329.1 | 309.1 | 263.0 |
| Paper | EU | 214.1 | 211.2 | 195.4 | 200.8 | 293.2 | 278.2 | 253.2 | 253.9 | 253.8 | 238.7 | 216.7 | 214.3 | 208.7 | 192.9 | 176.8 |
| 19, Coke | DE | 314.9 | 294.4 | 336.5 | 273.6 | 341.1 | 295.0 | 258.9 | 228.9 | 264.8 | 266.0 | 312.4 | 356.8 | 325.8 | 333.6 | 301.1 |
| | EU | 612.4 | 620.4 | 559.9 | 551.7 | 687.5 | 528.1 | 409.8 | 347.4 | 357.4 | 392.4 | 594.3 | 538.9 | 541.4 | 539.4 | 436.8 |
| 20 and 21, | DE | 377.7 | 361.0 | 368.0 | 347.2 | 351.4 | 337.8 | 311.9 | 331.5 | 320.4 | 318.0 | 321.0 | 315.8 | 297.9 | 261.2 | 224.7 |
| Chemicals | EU | 334.0 | 296.9 | 283.0 | 279.3 | 294.0 | 264.5 | 264.4 | 253.6 | 246.6 | 230.2 | 239.9 | 240.7 | 217.0 | 198.2 | 210.7 |
| 22, Plastic | DE | 162.5 | 158.3 | 160.3 | 153.9 | 157.7 | 152.7 | 131.7 | 136.3 | 136.0 | 128.9 | 122.6 | 120.7 | 110.6 | 98.5 | 83.0 |
| | EU | 77.8 | 77.2 | 72.4 | 70.7 | 76.9 | 77.7 | 68.3 | 69.8 | 77.8 | 71.7 | 64.3 | 65.6 | 60.2 | 57.0 | 50.8 |
| 23, | DE | 615.9 | 580.6 | 594.9 | 550.3 | 533.4 | 528.9 | 481.0 | 474.7 | 456.6 | 439.3 | 445.8 | 434.1 | 415.0 | 404.6 | 356.8 |
| Non-metallics | EU | 770.2 | 674.8 | 643.4 | 632.3 | 621.3 | 613.7 | 588.0 | 581.6 | 566.1 | 535.3 | 524.3 | 518.6 | 476.6 | 463.8 | 414.6 |
| 24, Metals | DE | 811.6 | 715.0 | 582.8 | 567.0 | 659.2 | 630.0 | 537.1 | 542.3 | 585.8 | 581.3 | 604.8 | 627.5 | 544.9 | 515.7 | 471.5 |
| | EU | 959.6 | 766.1 | 694.4 | 656.1 | 785.5 | 668.8 | 598.6 | 623.5 | 631.7 | 595.2 | 593.7 | 608.3 | 547.7 | 494.0 | 484.9 |
| 25 to 28, 33, | DE | 54.0 | 49.8 | 48.5 | 48.0 | 51.4 | 48.6 | 44.3 | 47.2 | 45.3 | 44.0 | 39.3 | 35.5 | 35.3 | 31.8 | 26.5 |
| Electr., machinery | EU | 62.2 | 56.8 | 51.9 | 48.8 | 51.9 | 50.2 | 46.4 | 43.8 | 42.6 | 38.0 | 37.9 | 37.2 | 36.0 | 34.1 | 30.7 |
| 29 to 32, | DE | 47.9 | 44.3 | 41.8 | 38.4 | 40.0 | 37.7 | 33.2 | 34.5 | 36.5 | 31.8 | 29.0 | 28.6 | 26.0 | 24.3 | 21.0 |
| Vehicles | EU | 33.5 | 32.4 | 31.0 | 31.3 | 31.9 | 31.4 | 29.6 | 29.6 | 28.9 | 25.0 | 22.3 | 20.0 | 19.5 | 19.1 | 17.0 |

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