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Searching for carbon leaks in multinational companies *

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Abstract

Does unilateral climate change policy cause companies to shift the location of production, thereby creating carbon leakage? In this paper, we analyse the effect of the European Union Emissions Trading System (EU ETS) on the geographical distribution of carbon emissions by multinational companies. The empirical evidence is based on unique data for the period 2007-2014 from the Carbon Disclosure Project, which tracks emissions of multinational businesses by geographical region within each company. Because they already operate from multiple locations, multinational firms should be the most prone to carbon leakage. Our data includes regional emissions of 1,122 companies, of which 261 are subject to EU ETS regulation. We find no evidence that the EU ETS has led to a displacement of carbon emissions from Europe towards the rest of the world, including to countries with lax climate policy and within energy-intensive companies. A large number of robustness checks confirm this finding. Overall, the paper suggests that modest differences in carbon prices between countries do not induce carbon leakage.

Keywords: EU Emissions Trading System, carbon leakage, multinationals, emissions, CDP

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1 Introduction

With the implementation of the European Union Emissions Trading System (EU ETS) and a range of other ambitious policies supporting the deployment of low-carbon technologies such as renewable energy, the European Union is widely perceived as the vanguard of climate change policy globally. However, this unilateral set of policies has raised concerns that EU governments are threatening the international competitiveness of Europe-based companies, in particular in carbon and energy intensive industries. This paper analyses a unique dataset to explore whether multinationals have displaced their carbon emissions from Europe towards the rest of the world when subject to carbon pricing. In a frictionless free-trade world economic model, the adoption of unilateral climate policies which increase the price paid by firms for their direct carbon emissions (or for carbon intensive inputs such as energy) relative to their foreign competitors would lead to a pollution-haven effect (Copeland and Taylor (2004); Levinson and Taylor (2008)): countries with relatively weaker regulations specialise in the production of carbon-intensive products in which they have a newly acquired competitive advantage, and subsequently export these back to "virtuous" countries. The relocation of economic activity toward less-regulated regions means that the policy is not only ineffective from a climate change point of view, but also costly from an economic point of view, by destroying jobs and economic activity in the more strictly regulated countries. This issue has been referred to as "carbon leakage" and has attracted a lot of attention both on the policy arena and in the recent literature (see Branger and Quirion (2014) and Fowlie and Reguant (2018) for recent reviews). Some authors (e.g. Baylis et al. (2014)) have also suggested that there could such a thing as negative leakage where carbon regulation in one sector or jurisdiction can lead to carbon reductions even in non-regulated ones.

In this paper, we explore the possibility of carbon leakage as a result of the EU ETS using a unique panel dataset tracking the geographical distribution of carbon emissions within 1,122 multinational companies. Multinational companies, with operations across a wide range of jurisdictions, might be particularly reactive to environmental regulations that impose higher production costs in a given location by shifting production to less regulated regions in which they already operate. Our data comes from the Carbon Disclosure Project (CDP), a non-profit data collection initiative established by the investment community to collect climate change-relevant data at the level of individual businesses, with the aim of understanding the exposure of companies to future climate change policies. The unique feature of the CDP data is that emissions of multinational businesses are broken down by country or geographical regions. Hence, we are able to study whether multinationals subject to the EU ETS reduce emissions in one location only to increase them elsewhere. Specifically, we compare emissions in Europe with emissions occurring outside Europe within the same company between 2007 and 2014.[1] We find no evidence that the EU ETS has led to a displacement of carbon emissions from Europe towards the rest of the world within multinational companies and rule out any leakage rate above 14%. A large number of robustness checks confirm this finding. Treated firms not only reduced emissions within the EU but also in third countries as a result of the regulation. This would explain the absence of carbon leakage, a conclusion which not only emerges for the average firm in our sample but also for various sub-samples, including - most importantly - for firms that are deemed by the European Commission to be particularly at risk of carbon leakage because they are highly carbon-intensive and/or trade-exposed.

The EU ETS was launched in 2005 and currently covers 31 countries across Europe (all 28 European Union Member States plus Iceland, Liechtenstein and Norway), 14,000 power stations and industrial facilities, representing roughly 40% of the EU's total greenhouse gas emissions, which are regulated according to their main carbon-emitting activity, such as combustion of fossil fuel, cement production or paper and pulp production. Firms that operate regulated installations make abatement and investment decisions according to the carbon price revealed in the market. An important feature of the EU ETS is that not all carbon-emitting installations operating in these sectors are regulated, in order to minimize

[1] The CDP dataset started in 2000, but the sample of firms included was extremely limited in the early vintages until 2006.

administrative costs. Activity-specific capacity criteria determine which installations are included in the EU ETS and which installations are exempt from regulation. This allows us to compare multinationals operating in Europe, only some of which own regulated installations. Since the beginning of the policy, there has been concern that the EU ETS would lead emissions and industrial activity to relocate outside of Europe, and the spectre of carbon leakage continues to influence key legislation such as the most recent EU Directive 2018/410.[2]

This paper contributes to the literature that seeks to understand the impact of unilateral climate change policies on carbon leakage (see Sato and Dechezleprêtre, 2015 and Dechezleprêtre and Sato, 2017 for recent reviews).[3] A large number of studies, based on Computable General Equilibrium (CGE) models (see Carbone and Rivers, 2017, for a review), find mix-evidence, highly sensitive to model assumptions and suggesting large levels of uncertainty. These studies have estimated a wide range of leakage rates associated to different emission reduction targets under the Kyoto Protocol, going from negative leakage due to spillover effects (e.g. Barker et al., 2007), to positive leakage rates, as high as 100%.

Compared to the extensive CGE literature, few empirical studies have sought to estimate the magnitude of the effect of climate change regulation on carbon leakage. Aichele and Felbermayr (2012) and Aichele and Felbermayr (2015) analyse the impact of carbon emissions reduction commitments under the Kyoto Protocol on the extent of bilateral trade flows and their carbon content, by sector. They find that signing of the protocol caused a 14% reduction in exports and a 8% increase in embodied carbon imports by committed countries from non-committed countries, suggesting that some carbon leakage is happening, especially in mostly affected sectors, such as basic metals, non-metallic mineral products, or paper and pulp. In a recent study, Ben-David et al. (2020) use variation in a composite index of environmental regulatory stringency across countries to ask whether environmental regulation induces firms

[2]Provision 10, for instance, states that "Experience gathered during the operation of the EU ETS has confirmed that sectors and subsectors are at risk of carbon leakage to varying degrees". Free allowance allocation is a direct consequence of this concern.

[3]See also Sato (2013) for a comprehensive review of the literature that seeks to measure the carbon content of trade.

to shift polluting activities abroad. They find that firms headquartered in countries with stricter environmental laws emit less greenhouse gas at home and more abroad.

In the absence of carbon pricing policies in most countries, changes in relative energy prices have provided an interesting source of variation to analyse the impact of unilateral climate change policy on production location and trade flows (Aldy and Pizer, 2015; Sato and Dechezleprêtre, 2015). These studies tend to find a small effect of energy price on net imports, with an elasticity between 0.1% and 0.8%, and only significant for energy-intensive industries.

Our paper is closely related to the limited number of studies that have sought to empirically assess the impact of the EU ETS on carbon leakage, focusing on different outcome variables, such as trade flows, business downsizing and foreign direct investments (see Martin et al., 2016 for a review). For instance, Naegele and Zaklan (2019) analyse the impact of the EU ETS on carbon emissions embodied in traded goods and on trade value, using data from the Global Trade Analysis Project (GTAP). They find no evidence that the EU ETS caused any increase in net imports (either in value or in terms of embodied carbon emissions). These findings confirm earlier insights on specific sectors (Branger et al. (2016) on the cement and steel sectors, and Sartor (2013) on the aluminum sector). Focusing on downsizing of businesses in Europe, Martin et al. (2014a) and Martin et al. (2014b), survey about 800 manufacturing firms in six EU countries. They find that firms regulated under the EU ETS are more likely than non-EU ETS firms to report that, in response to future carbon pricing, they would consider downsizing their operations in the EU, by up to 10 percent. Using administrative data for French manufacturing firms, Colmer et al. (2020) find that firms regulated in the EU ETS reduce carbon emissions by 8-12% in Phase 2, compared to unregulated firms, without a reduction in employment or value-added. Similar findings come from Dechezleprêtre et al. (2020), who use administrative data from France, the Netherlands, Norway, and the United Kingdom to find emissions decreases of 10% in European emissions of EU ETS-regulated firms. Furthermore, they find no impact of the

EU ETS on total imports of intermediate goods by regulated companies, whether measured by their value or by their carbon content.

Other studies have used firm-level data to investigate the impact of the EU ETS on foreign direct investment, which could be viewed as indicative of carbon leakage. Koch and Basse Mama (2016) use data from Germany and Borghesi et al. (2020) focus on Italy. Contrary to this paper, they do not have geographically disaggregated data on carbon emissions, and focus instead on whether the EU ETS led to increases of investment in unregulated (or less regulated) countries. Borghesi et al. (2020) find that the EU ETS had a small positive effect on the number of new subsidiaries abroad, but a larger impact on production taking place in foreign subsidiaries, especially in trade-intensive sectors. Koch and Basse Mama (2016) also find evidence that the EU ETS encourages outward FDI of German multinationals. However, the effect is concentrated on a small subset of firms that are less capital intensive and therefore likely to be more geographically mobile.

Our paper contributes to this literature by providing new evidence on the link between EU ETS regulation and carbon leakage. Thanks to the unprecedented data collection effort by the Carbon Disclosure Project (CDP), we are able to track firm level CO_2 emissions by geographical region for 8 years since 2007. Exploiting information on the country of origin of carbon emissions, we can directly assess the carbon leakage hypothesis by comparing trends of multinational firms' CO_2 emissions in Europe relative to non-European countries, depending on whether they are regulated by the EU ETS or not. The novelty of the research lies in our ability to track greenhouse gas emissions within multinational companies in all jurisdictions in which they operate. To the best of our knowledge we are the first to be able to do this.

The rest of the paper is structured as follows. The next section presents the empirical methodology and Section 3 describes the different datasets used, in particular the one obtained from CDP. Section 4 discusses the main results. Extensions and robustness tests are presented in Section 5. Section 6 provides concluding remarks.

2 Theory and methods

The main contribution of this paper is that it is the first to study leakage *within* firms. We define leakage from the EU by firm i as an increase in Rest of the World (RoW) emissions by firms in response to changes in EU carbon pricing τ; i.e.

$$\frac{\Delta CO2_i^{RoW}}{\Delta \tau} > 0$$

Of course there are other forms of leakage. In particular, leakage might occur externally to a given firm with EU firms losing global market share (along with emissions) while RoW are gaining. [4] This paper's focus on within firm leakage is made possible by having access for the first time to emissions data within multinational firms (MNEs). Moreover, because MNEs have already sunk the fix cost of operating in multiple countries we would expect them to react more strongly to carbon pricing than other firms.

In appendix C we develop a model which examines the mechanics of within firm leakage in more detail. This shows that the key factor determining the occurrence of leakage is a sufficient degree of technological substitutability between EU and RoW emissions. In particular, this elasticity of substitution between EU and RoW emissions (γ) must (in absolute terms) be higher than the elasticity of demand (η) the firm faces. If - on the other hand - $\eta > \gamma$, we might have what could be described as negative leakage where RoW emissions decline because of EU climate policy.[5] In such a case, there are not enough emissions being leaked to prevent a global cost and price increase for the multinational, and that reduces global demand. In addition, leakage can be determined by technology spillovers if carbon

[4] The IPCC (2007) defines it as "the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries". Graichen et al. (2008) distinguishes between two forms of leakage: investment leakage and operational leakage. The former follows in the medium-to-long run from the decision of firms to not expand their production facilities or failure to reinvest in the regulated region (the EU in this case). The latter describes the short-term reaction of production being stopped or decreased in the EU and relocated to other countries with no carbon pricing.

[5] Negative leakage has also been discussed by Baylis et al. (2014). They describe a somewhat different mechanism whereby carbon policy induced shifts between factors of production lead to increases in carbon mitigating and mobile capital. As a result, costs increase in both regulated and non regulated regions.

pricing induces investments in carbon mitigating technology and RD. These technological improvements can lead to technology changes and emission reductions throughout multinational firms' production sites, irrespective of the local regulatory regime. Our model shows that this can lead to non-trivial interactions between technology changes, the amount of carbon pricing and RoW emissions; e.g. if carbon taxes are too low firms might not find it profitable to engage in technology changes and only respond to carbon price increases by limited leakage. As carbon prices increase, firms will initially expand technology investments. If these spill over globally, this can lead to RoW emission reductions (i.e. negative leakage). However, if carbon prices are even higher, increasingly less production occurs within the EU. This in. turn reduces the incentive to invest in technology improvements, leading to positive leakage.

To study these issues empirically we exploit the carbon price differential introduced by the European Union Emissions Trading System (EU ETS) in a differences in differences setting (DiD); i.e. we compare changes in firms regulated by the ETS with firms that are not by running a regression of the form:

$$\Delta Y_{it} = \beta_1 ETS_i + \tau X_{it} + \epsilon_{it} \tag{1}$$

where ΔY_{it} are first differences of a variety of outcome measures which we discuss below, ETS_i is a dummy equal to 1 for EU ETS regulated firms and X_{it} is vector of control variables such as industry and time controls. Note that the EU ETS was introduced in 2005 however, as detailed in the next section, our data sample only starts in 2007. As a result, we cannot rely on a classic before and after design. In particular this means that we will not capture any impact of the ETS on leakage that would have occurred at the start of the scheme. However, in Phase I of the EU ETS from 2005-2007, emission caps were too generous and prices as a consequence very low. Crucially, banking of permits was not possible either. Hence, firms had very few incentives to either reduce or leak emissions. This changed in 2008 when caps were tightened and banking of permits was introduced. Related studies - e.g. Colmer et al. (2020) - suggest that only this more stringent policy design led to any impacts on emissions. Hence, if there are leakage effects we should find them from 2008 onwards, which aligns with our sample period.

As our main outcome variable we use the share of EU emissions in total global emissions of a firm; i.e.

$$Y_{it} = \frac{CO2_{it}^{EU}}{CO2_{it}^{EU} + CO2_{it}^{RoW}}$$

If carbon leakage is an issue, we would expect to find $\beta_1 < 0$ in a regression such as equation 1. Note that we can think of this as conservative approach because a negative β_1 is only a necessary condition for (positive) leakage to occur. Indeed, we could have $\beta_1 < 0$ with negative leakage where EU emission reductions are simply larger in the EU but still negative in RoW. Using emission shares as outcome variable can also help with any remaining unobserved heterogeneity. Differencing will remove fixed heterogeneity specific to a firm. Looking at the share of emissions will remove time varying firm specific heterogeneity that is shared by all subsidiaries of a given firm. Nevertheless, we also report regressions of both the level of EU and RoW emissions.

We estimate equation 1 on a variety of sub-samples and with various control variables to account for concerns about endogeneity as well heterogeneity in potential leakage effects. For instance, ETS firms by definition have to be located in the EU (at some point) whereas this is not the case for non-ETS firms. Moreover, ETS firms are mostly manufacturing firms or power plants. We address this issue by estimating equation (3) for a number of different subsets of the data. First, the sample is restricted to firms reporting non-zero emissions both inside and outside the EU, although not necessarily at the same point in time. Second, we only look at firms with non-zero EU emissions in the base year (t-1). Third, we focus on firms with non-zero EU emissions in the base year (t-1) *and* non-zero non-EU emissions at some point in our sample. In addition, the previous specifications are repeated restricting the sample to manufacturing firms. We further refine the analysis by running the regressions on a sub-sample of firms that belong to sectors deemed "at risk of carbon-leakage" by the European Commission (Emissions Trading Directive 2009/29/EC). Such sectors exceed certain thresholds in terms of carbon or trade intensity or both. Leakage effects would be expected to be particularly strong in such sectors (see Appendix E for a list of those sectors).

Note that firms in the EU, even within narrows sectors, are not all necessarily regulated by the EU ETS. There are sector specific firm level capacity thresholds which are high enough for us to observe control firms within the same sector and within the EU, even if we restrict the sample to firms with operations within the EU.[6]

3 Data

3.1 Main dataset

In order to implement the methodology described, we construct an unbalanced panel of firms for the period 2007-2014 by combining three different data sources. First, data on annual firm-level carbon emissions from the Carbon Disclosure Project (CDP), an NGO acting on behalf of over 600 institutional investors. CDP asks listed companies to disclose geographically-disaggregated information on carbon emissions.[7] The CDP data are unique: as far as we know, it is the only consistently available data source to track the geographical distributions of carbon emissions *within* multinationals. Second, data on turnover, assets, number of employees and sector of activity of these companies from ORBIS, one of the largest global financial firm-level databases provided by Bureau Van Dijk under a commercial license. Finally, we use the European Union Transaction Log (EUTL) to identify companies that own at least one installation regulated under the EU ETS. Identifying which multinational company is regulated by the EU ETS is not straightforward because of the challenge in

[6]see Colmer et al. (2020) for a detailed discussion of EU ETS inclusion.

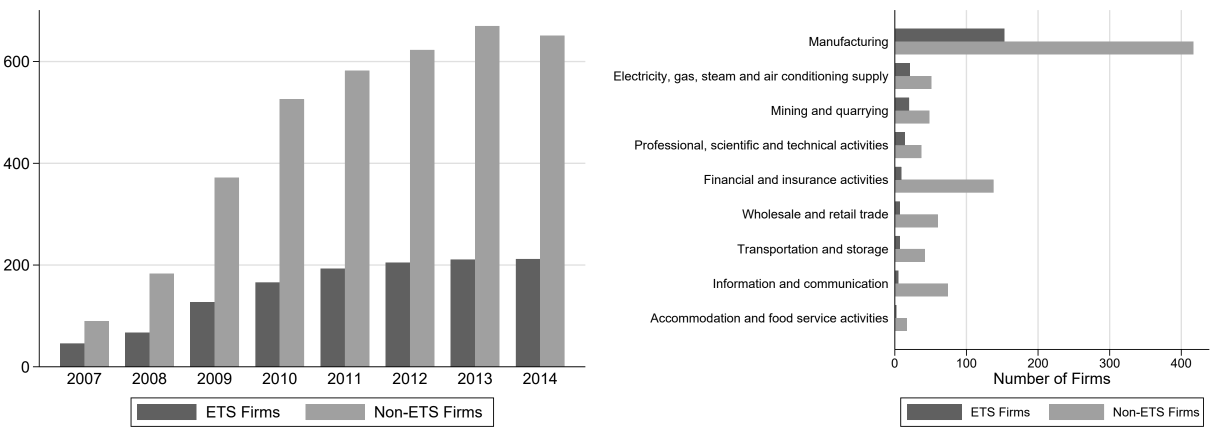
[7]The CDP has recently started to also include non-listed firms in its survey.

assigning EUTL installations to CDP multinationals through their ownership structures. The different steps taken to do so and to merge the different datasets are described in detail in Appendix A

As shown in panel (a) of Figure 1, the number of observations in the CDP grows in the initial years of our sample, and then remains above 800. The overall sample consists of 1,122 companies, 261 of which are regulated under the EU ETS.

Figure 1: Firms with Positive CO_2 in EU in Base Year

(a) Across Years (b) Across Industries



Panel (b) in Figure 1 displays the sectoral distribution of the companies in our sample, sorted by the number of EU ETS firms in a sector (in descending order). The sector assignment is based on the NACE Rev.2 code of the multinational firm. The majority of these companies are from the manufacturing sector, with other companies mainly operating in the banking and financial, ICT, and utilities sectors. As expected, the majority of EU ETS companies in the sample operate in manufacturing and the power sector.

It is important to keep in mind, however, that it is *activities* that are regulated under the EU ETS, not economic sectors, even if they sometimes closely overlap (e.g. cement production). As a consequence, companies operating in virtually any sector of the economy can be regulated by the EU ETS if, for example, they produce energy or heat on-site using carbon-emitting fuels such as gas, coal or oil. This explains why we find EU ETS-regulated companies in sectors such as financial and insurance activities or retail trade. In terms of the size of regulated EU ETS companies, we note that we focus on multinational firms. By definition, these firms a larger in size compared to the average EU ETS-regulated company. While this limits the external validity of our findings, on the other hand, it is precisely large multinational firms that are most prone to leakage, so results based on our sample should give an upper bound for the effect of the EU ETS on leakage in the average EU ETS-regulated firm.

The CDP offers unique data that allows us to implement our methodology, but with non-mandatory participation in the survey, a focus on listed companies, and self-reporting of emissions, concerns of selection and measurement biases might arise. Given the centrality of the data for our analysis, the next two sub-sections address these potential issues in detail.

3.2 Selection issues in the emissions data

We first address the selection concern by comparing whether multinationals that report emissions data to the CDP differ from those that do not, for the universe of multinationals that are regulated under the EU ETS. To do so, we first select from ORBIS all multinational firms active in the EU and in the same sectors as those represented in the CDP dataset. We identify multinational firms through the location of the subsidiaries they own[8]. We then select, within those multinational firms, those that have installations that are regulated by the EU ETS, as defined in the previous section. This allows us to obtain verified greenhouse gas emissions data for their European regulated installations from the EUTL. Within this dataset of all EU ETS-regulated multinational firms, we then assess whether those firms that respond to the CDP survey differ from those that do not[9]. As displayed in the first panel of Table 1, we find that regulated firms that reply to the CDP survey are larger on average.

[8]We apply an ownership threshold of 50% in defining these shareholder paths. Moreover, we only include firms that have non-missing data for revenue or total assets.

[9]Due to ORBIS data availability, this comparison can only be made from 2010 onward.

Table 1: Comparison of Surveyed Multinationals

	(1) Emissions	(2) Revenue	(3) Employees	(4) Assets
Dependent variable	ln of variable			
CDP	1.078***	3.176***	3.138***	3.546***
	(7.46)	(44.63)	(38.78)	(49.96)
Observations	6240	7758	7045	7785
Dependent variable:	Δ ln of variable			
CDP	-0.0129	0.0000358	0.00836	-0.00787
	(-0.18)	(0.00)	(0.73)	(-0.94)
Observations	4873	6113	5348	6139

NOTES: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. The dependent variable is verified carbon emissions in the EUTL in column 1, revenue in thousands of Euros in column 2, employees in column 3 and assets in thousands of Euros in column 4. In the upper part of the table, the dependent variable is the logarithm of these. In the lower part, it is the annual change of the logarithm.

This is true in terms of emissions in the EU, revenue, assets and employment. However, when considering the change of these variables in the second panel, it appears that multinational firms that respond to the CDP survey are no different to others. No self-selection according to differential trajectories in either emissions or economic indicators appears to be taking place. Given that our analysis is based on changes in emissions, we take Table 1 as evidence for the likely absence of a selection issue in our empirical framework.

It is also worth noting that there is an extensive literature studying the likelihood of companies to report their emissions in voluntary surveys. For example, some recent contributions (Reid and Toffel, 2009; Brouhle and Harrington, 2009; Matsumura et al., 2013) have shown that companies operating in cleaner sectors are more likely to report their environmental activity. This is also true for companies performing better relative to others in their sector. Reporting also increases with the proportion of reporting firms in the same sector. However, such issues are less of a concern with the CDP data. Firstly, while the CDP survey is not mandatory, firms have an additional incentive to participate because CDP acts as an agent for a group of large investment firms. This setup introduces a somewhat different reputational driver: refusal to take part could send a negative signal to potentially important investors and sources of finance for a firm (Kim and Lyon, 2011). Recent studies have shown that carbon emissions affect stock returns and firm value, with financial investors demanding a higher premium when perceiving a higher carbon risk (Matsumura et al., 2013; Bolton and Kacperczyk, 2020). Second, participating firms are given the choice to be featured in the outward facing CDP report or only to be included in background data and confidential reports to investors. We believe that this makes positive self-selection less likely since we use the whole CDP database, which consists both of publicly available data and unpublished reports. However, for the purpose of this study, these issues would only be a concern if they vary systematically between EU ETS and non-EU ETS firms, and across regions within each firm, and there seems to be no reason for that to be the case.

3.3 Consistency of the CDP emissions data

Since the CDP emissions data originate from a survey, there could be concerns about the consistency of the quality of response both across firms and over time, and the lack of verification of survey answers. Lack of consistency could imply that the emissions data might not contain enough signal to detect a leakage effect because of noise. Carbon reporting is a recent development, and different reporting methodologies currently coexist. While the CDP recommends the use of one particular reporting protocol (the WRI/WBCSD GHG protocol), multinationals are allowed to follow different reporting methodologies (Bellassen and Stephan, 2015). To assess the consistency of the outcome data, we use the CDP emissions data for the European subsidiaries of EU ETS multinationals and correlate it to the verified emissions data obtained from the EUTL. This comparison is invariably coarse, because multinationals may operate both regulated and unregulated installations, so that a perfect correspondence cannot be expected. Nevertheless, we expect to find a clear and significant relationship between the two. To do this, we use the verified emissions for each EUTL installation belonging to a multinational firm and aggregate them at the multinational level.

We weight the emissions by the percentage of the shares that the multinational owns in a subsidiary. To illustrate: a multinational that owns 50% of all shares of a subsidiary would be assigned 50% of that subsidiary's emissions. This weighting strategy corresponds to the guidelines in the Climate Change Reporting Framework used by the CDP survey that instructs multinationals to weight greenhouse gas emissions in joint ventures by ownership percentage. For this analysis, we compute the correlation of these verified emissions to the emissions data reported in the CDP survey. We do so by aggregating emissions to the European level for each multinational.

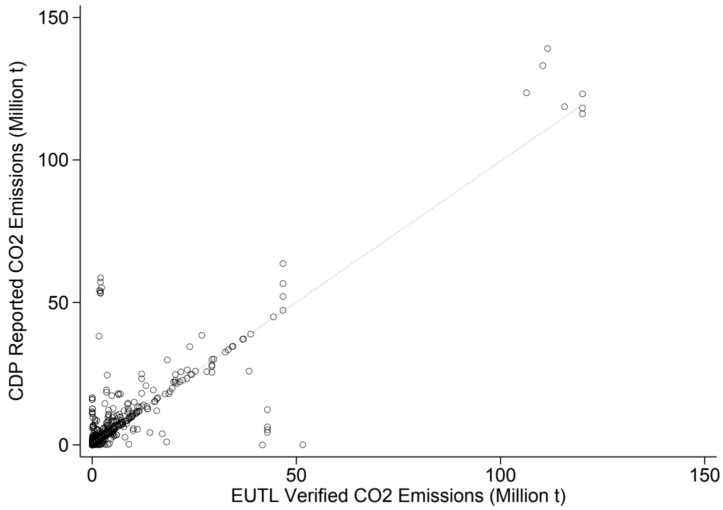
Figure 2 below shows that there is a strong correlation of 0.88, and a slope coefficient of close to 1. In other words, the CO_2 emissions reported in the CDP survey are an accurate reflection of the underlying reality, as reported in EUTL data verified by third party auditors[10]. The correlation is also statistically significant: while there are some obvious outliers, a linear regression of reported emissions on the verified emissions with cluster-robust standard errors, where multinationals are the units of clustering, yields a t-statistic of 13.71. We interpret this as an additional indication that the quality of the CDP data is sufficient for our analysis.

There is still substantial noise in the CDP data, but this is to be expected for the following reasons: (i) the matching process between CDP companies and EU ETS-regulated installations is inevitably an approximation; (ii) not all companies report greenhouse gas emissions alike and they need to be consistently applying existing guidelines; and (iii) in a limited number of cases, multinationals only report total European emissions in the CDP survey, rather than emissions broken down by countries, making it difficult to compare emissions on a like for like basis.

Finally, we find below in Section 5.3.1 that by using the carbon emissions reported in the CDP survey to estimate the emissions reduction induced by the EU ETS, we find figures of

[10]The reason to assess the consistency in levels rather than in changes is twofold: to directly illustrate the measure we use in the robustness check for treatment assignment in section 5.1, and because a correlation in levels is a more demanding consistency check than a correlation in the rate of change.

Figure 2: Consistency of CDP Reported CO_2 Emissions Data



Note: Corr: 0.88; Coeff: 0.99; t-stat: 13.71 (cluster-robust SEs)

the same order of magnitude than those found by Colmer et al. (2020) that use administrative French data and by Dechezleprêtre et al. (2020) who use administrative data from France, the Netherlands, Norway, and the United Kingdom . This provides additional indication that the CDP emissions data is consistent with administrative sources of data that can be considered more reliable. In light of these different considerations, we now turn to presenting the results of our analysis.

4 Main results

The sample resulting from our data collection and compilation is described in Table 2 and consists of 1,122 multinational companies[11]. The average share of CO_2 emissions within Europe across our sample is 34%.

In Table 3, we compare ETS and non-ETS companies using simple t-tests. Not surprisingly, ETS firms emit more both in European and in non-European countries. They are on

[11]There are 9 firms for which there is no operating revenue data available in ORBIS, 16 firms for which total assets are missing and slightly more than a hundred firms for which employment is missing.

Table 2: Descriptive Statistics

	(1) Mean	(2) Stand. Dev.	(3) N. firms	(4) Obs.	(5) Source
CO_2 Emissions within Europe (Million t CO_2e)	1.26	9.86	1,122	4,924	CDP
CO_2 Emissions outside Europe (Million t CO_2e)	3.07	12.37	1,122	4,924	CDP
Share of CO_2 Emissions within Europe	34%	39%	1,122	3,802	CDP
Δ Share of EU emissions	-0.01	0.09	1,122	3,802	CDP
Operating Revenue (Million Euros)	12940.85	24503.95	1,113	4,889	ORBIS
Total Assets (Million Euros)	55180.93	198541.37	1,106	4,850	ORBIS
Employees (in Thousands)	44.11	94.28	1,000	4,430	ORBIS
ETS Price (Euros/tCO_2)	10.07	3.39	1,122	4,924	EU ETS
Climate Laws, Institutions and Measures Index (CLIMI)	0.30	0.16	1,122	4,924	EBRD

average characterized by a higher turnover, a higher number of employees and higher assets. About 60% of the emissions of ETS-firms tend to be located in Europe. While this number is slightly lower for non-ETS firms. A look at the full firm-level distribution of the share of emissions in Europe, displayed in Figure 3, shows the large overlap across both groups of multinationals, suggesting that the non-ETS firms in our sample are in fact a relevant control group. The figure displays our preferred sample which includes only non-ETS multinationals that report positive emissions in the European Union in the CDP survey.

Figure 4 provides a graphical summary of our main findings relating to the growth of emissions. It reports the joint bi-variate distribution of the growth in CO_2 emissions in the EU versus the Rest of the World (RoW) at the level of firms (see equation 4). Panel (a) shows the distribution for all firms with non-zero EU emissions in the base year. Panel (b) reports only EU ETS-regulated firms. Panel (c) overlays contour plots from both distributions. Looking first at Panel (a), we see that the distribution is concentrated primarily around zero, implying that for most firms, the levels of carbon emissions are mostly stable over time. There is also a notable mass of firms with positive growth in both EU and RoW emissions. Panel (b) suggests that emission growth is more heterogeneous in ETS firms. However, there is little evidence of such firms simultaneously reducing EU and increasing RoW emissions. Negative emission growth in the EU is rather associated with negative emission growth in the RoW as well. Hence, this indicates either genuine emissions reduction efforts globally or a decline of economic activity in these sectors rather than carbon leakage activity.

Table 3: ETS vs. non-ETS Firms

	ETS Firms	Non-ETS Firms	Difference
Panel A: All Firms (N= 1,122)	238	884	
CO_2 Emissions within Europe	5.68	0.07	5.61***
(Million tons CO_2e)	(20.82)	(0.46)	[0.00]
CO_2 Emissions outside Europe	4.34	2.72	1.61*
(Million tons CO_2e)	(12)	(12.45)	[0.07]
Share of CO_2 Emissions within Europe	53.47%	28.3%	25.16%***
	(0.36)	(0.37)	[0.00]
Δ Share of EU emissions	-0.7%	-0.9%	-0.1%
	(0.08)	(0.09)	[0.82]
Operating Revenue	25683.52	9474.84	16208.68***
(Million Euros)	(37364.24)	(18142.07)	[0.00]
Total Assets	65353.97	52421.34	12932.63
(Million Euros)	(200098.8)	(198142.61)	[0.37]
Employees	64.19	38.34	25.84***
(in Thousands)	(84.31)	(96.23)	[0.00]
Climate Laws, Institutions and Measures Index	0.24	0.30	-0.06***
(CLIMI)	(0.16)	(0.16)	[0.00]
Panel B: Manufacturing Firms (N=571)	154	417	
CO_2 Emissions within Europe	1.72	0.02	1.69***
(Million tons CO_2e)	(6.34)	(0.18)	[0.00]
CO_2 Emissions outside Europe	2.93	1.26	1.66***
(Million tons CO_2e)	(9.84)	(5.73)	[0.01]
Share of CO_2 Emissions within Europe	48.85%	22.25%	26.59%***
	(0.34)	(0.32)	[0.00]
Δ Share of EU emissions	-0.2%	-0.5%	0.3%
	(0.09)	(0.11)	[0.74]
Operating Revenue	24099.02	7331.53	16767.48***
(Million Euros)	(35754.96)	(12192.53)	[0.00]
Total Assets	36028.31	9024.81	27003.49***
(Million Euros)	(60873.86)	(14050.55)	[0.00]
Employees	65.05	27.29	37.76***
(in Thousands)	(79.40)	(41.50)	[0.00]
Climate Laws, Institutions and Measures Index	0.27	0.34	-0.06***
(CLIMI)	(0.15)	(0.13)	[0.00]
Panel C: Manufacturing Firms at Risk of Carbon Leakage (N=444)	114	330	
CO_2 Emissions within Europe	1.54	0.03	1.51***
(Million tons CO_2e)	(3.63)	(0.21)	[0.00]
CO_2 Emissions outside Europe	2.8	1.37	1.43***
(Million tons CO_2e)	(7.59)	(6.13)	[0.04]
Share of CO_2 Emissions within Europe	50.35%	20.7%	29.65%***
	(0.34)	(0.3)	[0.00]
Δ Share of EU emissions	0.1%	-0.4%	0.6%
	(0.09)	(0.11)	[0.55]
Operating Revenue	20547.37	7749.52	12797.85***
(Million Euros)	(32122.19)	(13032.47)	[0.00]
Total Assets	31059.39	9453.2	21606.19***
(Million Euros)	(59035.29)	(145909.78)	[0.00]
Employees	54.50	28.20	26.3***
(in Thousands)	(66.66)	(43.08)	[0.00]
Climate Laws, Institutions and Measures Index	0.28	0.34	-0.06***
(CLIMI)	(0.15)	(0.13)	[0.00]

NOTES: Means and standard deviations are reported in parenthesis. The p-value for the difference is reported in square brackets in column (3) and taken from a two-sided t-test with equal variances. ***p< 0.01, **p< 0.05, *p< 0.1. Firms at risk of carbon leakage are CDP companies operating in sectors deemed at risk of carbon leakage by the European Commission. Manufacturing firms are firms coded as "C-Manufacturing" in the NACE Rev.2 Main Section classification. The number of firms N in Panels A-C refers to the total number of firms in the sample. Not all firms report all firm level characteristics. Sample is restricted to firms that report positive emissions in Europe when first reported in CDP.

Figure 3: Comparability of treated and control firms

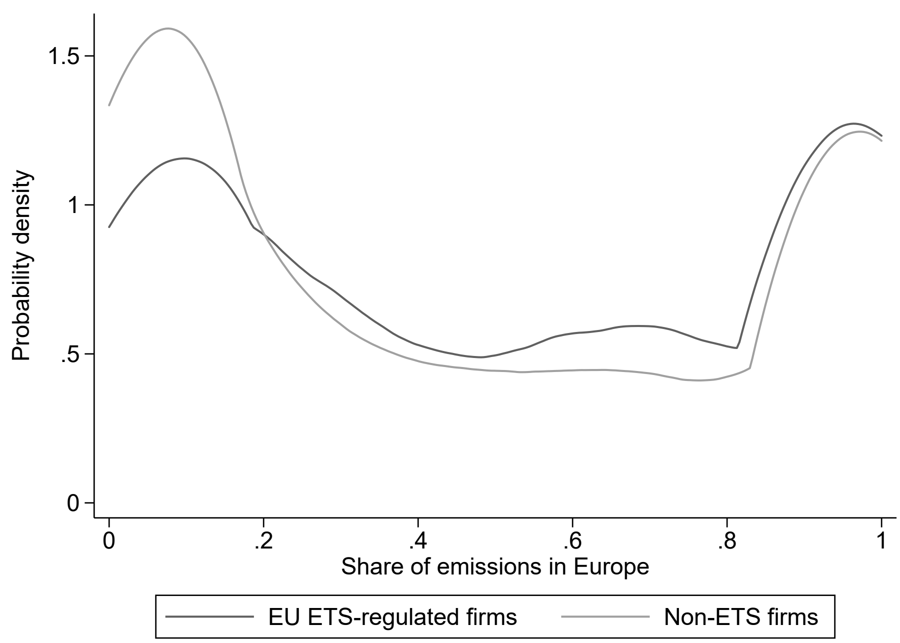
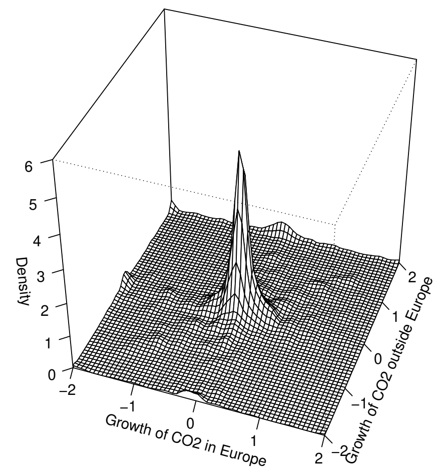
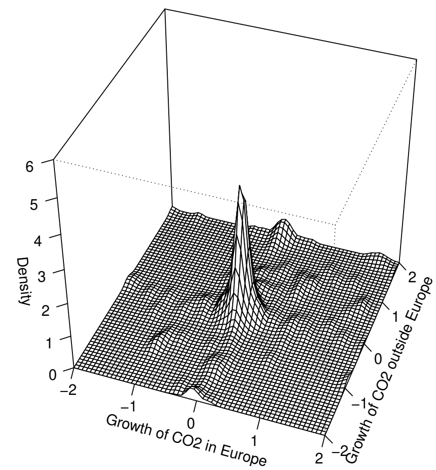


Figure 4: The Joint Distribution of Changes in CO_2 Emissions - EU vs RoW

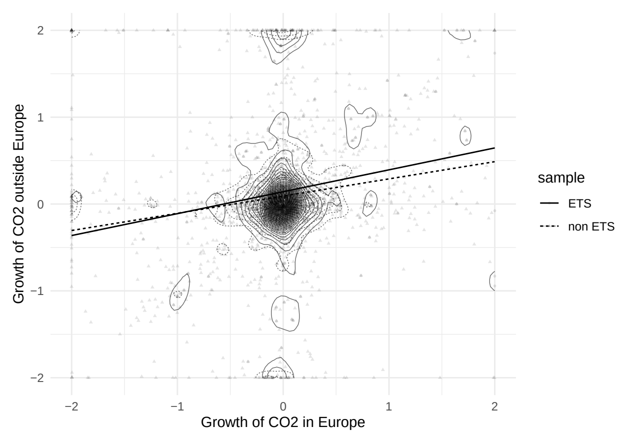
(a) Firms with Positive CO_2 in EU in Base Year



(b) ETS firms



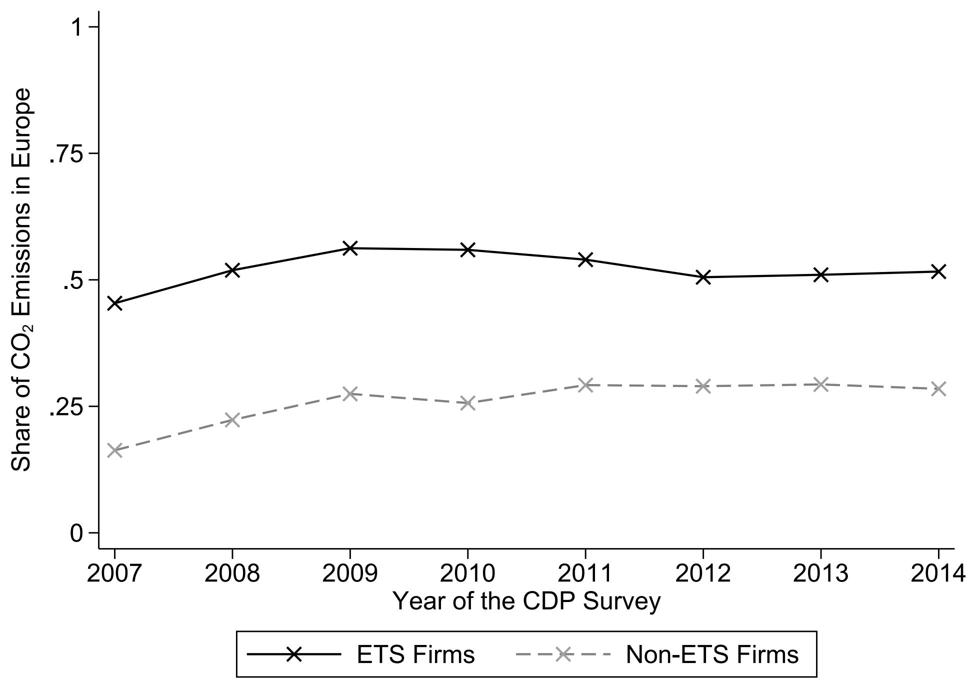
(c) Overlaid Contour Plots



Note: The figure reports the joint bi-variate distribution of the growth in CO_2 emissions in the EU versus the rest of the world (RoW) at the firm-level. First panel: all firms with non-zero EU emissions in the base year. Second panel: only EU ETS-regulated firms. Third panel: overlayed contour plots from both distributions. To deal with firms reporting 0 emissions in some years, we compute growth rates as $g_{it} = \frac{CO2_{it} - CO2_{it-1}}{0.5(CO2_{it} + CO2_{it-1})}$

Figure 5 displays the share of CO_2 emissions in Europe over the period 2007-2014 for the full sample of ETS and non-ETS firms respectively. It is consistent with the evidence presented in Table 3, showing that ETS firms generate a larger share of emissions in Europe compared to non-ETS firms. From 2007 to 2009, the share of European CO_2 emissions grows slightly for both ETS and non-ETS firms. It then remains fairly constant afterwards for both groups of multinationals. The gap between the two types of firms then remains stable over the period 2007-2014. If anything, we observe that non-EU ETS firms increase their share of emissions in Europe over time, while that share remains stable for EU ETS firms.

Figure 5: Share of CO_2 Emissions in Europe for ETS and non ETS Firms



Turning to the results relative to the share of EU emissions, Table 4 reports the estimates of equation (3) with the dependent variable being the change in the share of EU emissions. Panel A reports the results for all firms in our sample, Panel B restricts the sample to manufacturing firms only and Panel C presents the results for firms in sectors considered at risk of carbon leakage by the European Commission.

Table 4: Regressions of the share of emissions in EU

Dependent variable:	Δ Share of EU emissions			
	(1)	(2)	(3)	(4)
Sample composition:	All	EU>0 RoW>0 any	EU>0 in t=1	EU>0 in t=1 RoW>0 any
Panel A: All Firms				
ETS	-0.00379	0.000934	0.00429	0.00396
	(-0.84)	(-0.15)	(0.71)	(0.58)
Observations	3802	2589	2441	2134
Number of firms	1122	676	683	568
R^2	0.00481	0.00871	0.00922	0.0128
Panel B: Manufacturing Firms				
ETS	-0.00179	0.000155	0.00407	0.00451
	(-0.28)	(0.02)	(0.49)	(0.50)
Observations	2007	1496	1305	1196
Number of firms	571	388	360	318
R^2	0.00743	0.0113	0.0129	0.0143
Panel C: Manufacturing Firms at Risk of Carbon Leakage				
ETS	0.00136	0.00294	0.00644	0.00657
	(0.17)	(0.30)	(0.59)	(0.56)
Observations	1147	830	706	656
Number of firms	328	220	201	180
R^2	0.00736	0.0108	0.0118	0.0129

NOTES: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. Column 1 includes all firms in the sample. Column 2, firms that have positive emissions in both EU and RoW in some year. Column 3, firms with positive EU emissions in the first period for which the company answered the CDP survey (t=1). Column 4 with positive EU emissions in t=1 and non-zero RoW emissions at some point over the sample.

Moving through the columns of Table 4, we impose different restrictions regarding regional presence of firms. Column 1 includes all firms. In column 2, we only include companies reporting positive emissions in *both* the EU and the RoW, although not necessarily at the same time. Column 3 includes only observations from companies with positive EU emissions in the first period for which the company answered the CDP survey. Finally, column 4 includes firms with positive EU emissions in the first period *and* non-zero emissions in the RoW at some point over the sample. The sub-samples created by cycling through both the panels and columns of Table 4 serve two purposes. Firstly, by restricting the sample to manufacturing firms or firms with non-zero EU emissions in their first year, we make the control group of non-ETS firms more similar to firms regulated by the ETS.[12] Secondly, by focusing on sectors supposedly at risk of carbon leakage or firms with both EU *and* RoW emissions, we investigate the potential heterogeneity of leakage effect between firms. Specifically, we would expect leakage effects to be more severe in groups deemed at risk of carbon leakage by the European Commission.

Looking at the different point estimates, we see that the coefficient on the ETS indicator is insignificant throughout Table 4. Furthermore, it is estimated to be remarkably close to 0, compared to the -0.09 average decrease in the share of CO_2 emissions in Europe for EU ETS firms. The point estimate is slightly positive for all the subsamples, but we can never reject the hypothesis that it is equal to zero. The highest positive coefficient estimate - though still insignificant and small - in all Panels is in column 4, i.e. for companies that report positive CO_2 emissions in an EU ETS-regulated country in the first period and positive CO_2 emissions in RoW at some point. This is the group of firms for which a leakage effect would be most expected. Therefore we do not find any evidence of a leakage effect, which would be characterized by a negative and statistically significant coefficient.

In the other columns we find that our point estimate is positive, but it is not statistically significant at the 10% level. It is instructive, however, to ask what a positive coefficient

[12] A company can only be regulated by the EU ETS if its installations emit within the EU.

would imply, hypothetically speaking. Two possible explanations spring to mind. Firstly, as discussed in more detail in Appendix C, there might be offsetting region-specific productivity shocks that are much stronger than the carbon price shocks implied by the ETS. Secondly, we have to bear in mind that the European Commission is classifying sectors at risk of leakage in order to target risk-mitigating policy measures. Specifically, sectors “at risk” are receiving freely allocated emission permits. Hence, a positive effect could imply that this policy is particularly successful to an extent that borders on “reverse leakage”. At any rate, our results indicate a zero effect.

5 Extensions and robustness

In this section, we present a range of robustness checks and extensions which together support our finding of no leakage.

5.1 Robustness to treatment assignment

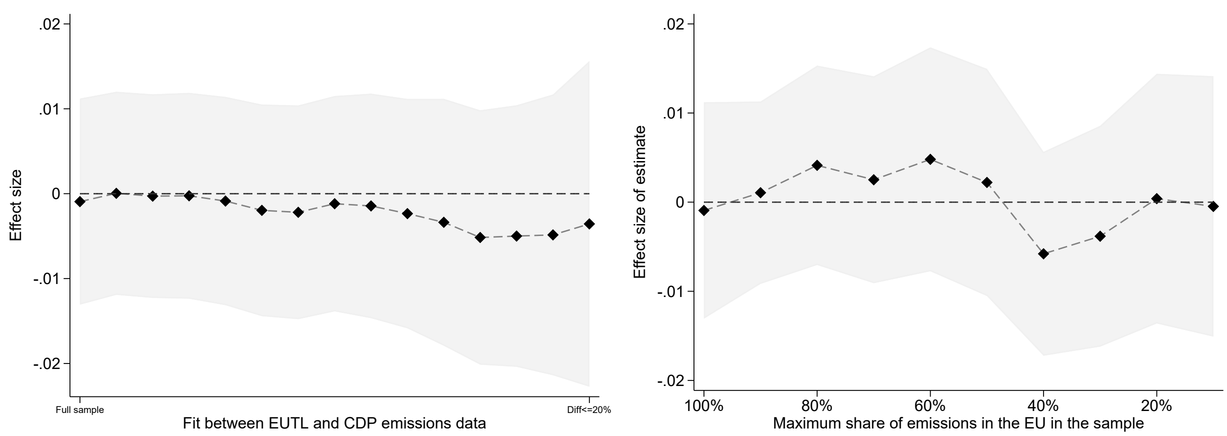
We first address the potential measurement error in treatment assignment. Since we match firm level data from the CDP dataset to EU ETS installations via ORBIS to obtain treatment status, there is likely to be some amount of noise that this process introduces for treatment assignment. Mis-assignment of treated installations to multinationals will bias our estimates towards zero.

To rule out measurement error on treatment assignment as an explanation for our null result, we re-estimate the treatment effect of our preferred specification from Table 4, Panel A, Column 2 with different subsamples. We exploit the fact that, as described in Figure 2, section 3.3, we have for each firm a measure of the consistency between the CDP and EUTL emissions. We can assume that if reported emissions from both datasets are similar, there was less noise in the matching process assigning EU ETS installations to CDP multinationals. We therefore run the regression with 15 different samples, reducing in each step the accepted difference in reported emissions and restricting as such the sample. This allows us to study how the estimated effect size changes with the quality of the match. If measurement error on treatment is a concern, the effect size would change as we increasingly restrict the subsample.

Figure 6, panel (a) shows that this is not the case. Instead, the point estimate for the effect size is remarkably stable for all subsamples starting from the full sample (the leftmost observation), all the way to the most restricted subsample that only considers observations for which the CDP and the EUTL emissions differ by at most 20%[13]. This means that the miss-assigned treatment status is unlikely to explain the null result of no carbon leakage as a result of the EU ETS.

Figure 6: Estimated effect size and treatment assignment

(a) Matching quality | (b) Treatment intensity



Note: The figure reports the effect size for the specification in Table 4, Panel A, Column (2). Left panel: each data point represents the specification for a different subsample based on the fit between the CDP and EUTL emissions data. Right panel: each data point represents the specification for a different subsample based on the maximum share of emissions of the firm in the EU when it first entered the CDP survey.

As an additional robustness check, we run the same specification, but this time restricting the sample based on the share of the total emissions that the firms emit in the EU when they enter the CDP survey for the first time. The results are shown in the right panel of

[13] The confidence intervals, in light grey, widen as expected due to the reduced sample size.

Figure 6. Starting with the whole sample, the result remains insignificant when we vary the sample down to firms that do not have more than 20% of their emissions in the EU.

5.2 Climate policy stringency in non-European jurisdictions

To further explore the heterogeneity of our results, we consider whether the stringency of climate policy in non-EU regions in which they operate might affect the impact of the EU ETS on the carbon leakage of multinationals. In particular, companies that face a less stringent climate policy in other regions of operation might have a higher incentive to displace emissions outside of Europe in response to the EU ETS. We use the EBRD's Climate Laws, Institutions and Measures Index (CLIMI) that measures the stringency of climate policy regulation in each country. First, we compute an average CLIMI for different regions in the world, by weighting the CLIMIs of each country within a given region with its GDP levels in the initial period. As shown in section B in the Appendix, this regional measure displays significant variation: Europe is the region with the most stringent climate regulation, while the region corresponding to former USSR as well as North America both score at the bottom of our weighted index. Oceania's and Asia's CLIMIs are close to the world average, driven by Australia and China in the respective regions. Both countries increased their policy effort to tackle climate change at the end of our sample period (before Australia abolished its carbon tax in 2014).

Based on these, we construct a company-specific CLIMI Index. We weigh the CLIMIs of the non-European world regions in which the company operates. The weight used for each region is computed as the share of the company's emissions in that region in the first year for which geographically disaggregated emissions are reported for the firm[14]. Each firm's specific measure captures the extent to which the individual company is exposed to a stringent regulation outside Europe. In this section, we explore whether the share of EU emissions is influenced by the climate stringency companies face outside the EU in regions

[14]The share is computed only relative to the emissions that each company produces outside Europe.

they are active in, depending on whether they are EU ETS-regulated companies or not. We test this hypothesis by estimating an augmented version of equation (1):

$$\begin{aligned}\Delta s_{it}^{EU} = \; & \beta_1 ETS_i X LowRegulation_i + \beta_2 ETS_i + \beta_3 LowRegulation_i \\ & + \beta_4 timestep_{it} + \gamma CDPvintage_t + \eta industry_i + \tau X_{it} + \epsilon_{it}\end{aligned}$$

where $LowRegulation_i$ is a dummy equal to one if the company-specific weighted CLIMI is below the median of the sample distribution, which indicates companies that are exposed to a less stringent climate policy outside Europe. $ETS_i X LowRegulation_i$ is the interaction between the ETS dummy and the Low Regulation dummy. A significant coefficient on the interaction term would indicate the presence of heterogeneous effects of the EU ETS on companies which are more or less exposed to stringent climate regulation outside Europe. Table 5 below reports the results of this exercise where we estimate this specification for different sub-samples. Column 1 presents results for the whole sample of firms emitting outside the EU, the second column focuses on the manufacturing sector, and column 3 narrows the sample even further to firms that are in the manufacturing sector and in a sector defined as at risk of carbon leakage. We find that being active in non-EU regions with less stringent climate policy does not increase the likelihood to reduce the share of EU emissions. The coefficient is negative but not statistically significant at conventional levels.

5.3 On the power of the null result

In our main results we do not find a significant difference in EU emissions share trends between ETS and non-ETS firms. We conclude that we cannot reject the hypothesis that there is *no* carbon leakage due to the EU ETS.

Naturally, such a null result raises the question as to the chances of detecting leakage

Table 5: Regressions of the share of emissions in EU - Climate Stringency

Dependent variable:	Δ Share of EU emissions		
	(1)	(2)	(3)
Sample composition:	All	Manufacturing	Manufacturing + at Risk of CL
$ETS \times LowRegulation$	-0.00335	-0.0118	-0.0232
	(-0.29)	(-0.71)	(-1.13)
ETS	0.00576	0.0166	0.0269
	(0.57)	(1.14)	(1.48)
$LowRegulation$	0.0420***	0.0541***	0.0598***
	(5.87)	(4.67)	(4.00)
ln (Revenue)	0.0106*	0.0216	0.0178
	(1.83)	(1.39)	(1.16)
ln (Assets)	-0.00659	-0.0223*	-0.0186
	(-1.54)	(-1.66)	(-1.56)
ln (Employment)	-0.00198	0.00260	-0.000129
	(-0.76)	(0.56)	(-0.02)
Observations	2393	1433	793
Number of firms	623	371	210
R^2	0.0249	0.0305	0.0255

NOTES: t statistics in parentheses. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. Only firms that have positive emissions in both EU and RoW in some year are included. Columns 1, 2 and 3's samples are respectively equivalent to Panels A, B and C of Table 4's column 2 but adding balance sheet controls.

in our data, if leakage was actually happening. In other words, what is the statistical power of our approach? To gauge this question we pursue three different approaches in this section: first, compare our findings for Europe based on the CDP data with findings from administrative emissions data. Second,we calculate the maximum amount of emissions leakage that we cannot reject statistically. Third, we explore the substantial variation in the price of EU ETS allowances through time over our sample period to estimate how sensitive leakage might be to price. All three lines of enquiry point towards a strong null result.

5.3.1 Regressions of the level of emissions

In a first robustness analysis to challenge our null result, we establish whether trends in emissions levels are different across regulated and non-regulated firms in three jurisdictions: the EU, RoW, and the world, i.e. the EU and RoW combined. In Table 6, we report regressions of changes in the level of EU, RoW and global emissions on an ETS treatment indicator. This reveals a significantly lower emissions trend for EU emissions of regulated EU ETS multinationals. These effects are economically meaningful; e.g. in column 1 where we report results for our full sample we find average reductions of 8.7% (calculated as 0.515/5.948). This result is quantitatively similar to the findings by Colmer et al. (2020) and Dechezleprêtre et al. (2020), which provides reassurance concerning the reliability and representativeness of our dataset. On the other hand, despite finding such strong CO_2 reductions of emissions within the EU, Panel B shows that we find no significant effects on RoW emissions of EU ETS-regulated multinationals. If EU emissions reductions that we measure were to leak, we would expect to find equivalent increases in RoW emissions, but the point estimates are 5 to 20 times smaller in absolute magnitude across columns. Taken together, the first and second panel provide an additional piece of evidence against carbon leakage being driven by the EU ETS. Finally, when looking at global emissions in the third panel, we do not find significant reductions but the point estimates are close to the EU emissions estimates, which reflects the relatively large EU share in emissions of multinationals in our sample. On balance, this

Table 6: Regressions of Emission Levels

	(1)	(2)	(3)	(4)
Sample composition:	All	EU>0 RoW>0 any	EU>0 in t=1	EU>0 in t=1 RoW>0 any
Dependent Variable	Δ Emissions EU			
ETS	-0.515*	-0.414**	-0.424**	-0.488**
	(-1.85)	(-2.51)	(-2.40)	(-2.50)
Average for ETS firms	5.948	5.761	6.383	6.196
Dependent Variable	Δ Emissions RoW			
ETS	0.107	0.0232	0.0797	0.0975
	(0.56)	(0.16)	(0.59)	(0.63)
Average for ETS firms	4.925	6.043	5.273	6.072
Dependent Variable	Δ Emissions Global			
ETS	-0.408	-0.391	-0.344	-0.390
	(-1.06)	(-1.63)	(-1.43)	(-1.43)
Average for ETS firms	10.87	11.80	11.66	12.27
Observations	3802	2589	2441	2134
Firms	1122	676	683	568

NOTES: t statistics in parentheses. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. Column 1 includes all firms in the sample. Column 2, firms that have positive emissions in both EU and RoW in some year. Column 3, firms with positive EU emissions in the first period for which the company answered the CDP survey (t=1). Column 4 with positive EU emissions in t=1 and non-zero RoW emissions at some point over the sample.

suggests that multinationals behave as if EU and RoW were fairly independent jurisdictions rather than being substitutes, as the carbon leakage hypothesis would have suggested. When looking at global emissions with noise from RoW emissions added, we find the same quantitative effect with a higher statistical error. These results are highly consistent with the idea that substitution of emissions between Europe and the rest of the world has not been taking place.

5.3.2 An upper bound for leakage

As a sensitivity analysis, we explore an extreme case: we measure the highest leakage effect that we cannot statistically reject and compare the amount of implied leakage to aggregate

Table 7: Counterfactual calculations

Dependent variable	Δ Share of EU Emissions			
	(1)	(2)	(3)	(4)
Sample composition	All	EU>0 RoW>0 any	EU>0 in t=1	EU>0 in t=1 RoW>0 any
ETS point estimate	-0.00379	0.000934	0.00429	0.00396
	(-0.84)	(-0.15)	(0.71)	(0.58)
ETS lower bound estimate	-0.0127	-0.0131	-0.00755	-0.00945
Upper bound leakage share in reductions 2008-2014	13.63%	14.40%	6.41%	8.77%

Notes: t statistics in parentheses. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. Column 1 includes all firms in the sample. Column 2, firms that have positive emissions in both EU and RoW in some year. Column 3, firms with positive EU emissions in the first period for which the company answered the CDP survey (t=1). Column 4 with positive EU emissions in t=1 and non-zero RoW emissions at some point over the sample.

emission reductions of EU ETS-regulated multinationals. As reported in the previous subsection, these firms reduced their emissions in Europe. Given this result, can we attribute a share of these reductions to carbon leakage? In our empirical strategy, as specified in equation (1), we would have concluded that leakage had occurred if $\beta_1 < 0$. Here, we revisit our main results from Table 4. For each specification reported in the table, we compute the largest value c, such that the hypothesis test of $H0 : \beta_1 <= -c$; $H1 : \beta_1 > -c$ would be inconclusive. Hence, we seek the smallest threshold, $-c$, that we cannot reject at a significance level of 5%, i.e. the biggest leakage effect that our data cannot statistically rule out, or the lower boundary of a 90% confidence interval of our estimate of β_1 in equation 1. We report those lower bound EU ETS (upper bound leakage) effect estimates in Table 7, along with our original point estimates. We find that we cannot reject EU ETS leakage effect estimates of between $\hat{\beta}_1^c = -0.0127$ and $\hat{\beta}_1^c = -0.00755$ (implying that the EU share would decline by between 1.27 and 0.755 percentage points more in ETS firms).

To get a sense of the environmental magnitude of this result, we compute a counterfactual level of emissions that would be implied by these effects over our sample period. First, for firm i in year t, we compute the counterfactual share of EU emissions, $s_{it}^{EU,CF}$ as: $s_{it}^{EU,CF} =$

$s_{it}^{EU} - \hat{\beta}^c ETS_i \times (t - t_0)$, where t_0 is the start of our sample period (2008) and, ETS_i indicates whether the firm is regulated by the EU ETS. For this exercise, we assume that the only thing that changes as a consequence of leakage, is the amount of emissions in the EU vs RoW but that the total amount of emissions, $CO2_{it}$, is unchanged in the counterfactual. It is a strong assumption, made as part of our extreme counterfactual exercise: drops in emissions in Europe for reasons other than relocation are also counted as carbon leakage, even when those had no impact on RoW emissions. This means that: $s_{it}^{EU,CF} = \frac{CO2_{it}^{EU,CF}}{CO2_{it}}$, hence $CO2_{it}^{EU,CF} = s_{it}^{EU,CF} \times CO2_{it}$. We therefore estimate the amount leaked from Europe as:

$$l_{it}^{EU} = CO2_{it}^{EU,CF} - CO2_{it}^{EU}$$

To assess if leakage is high or low, we compare this to an estimate of the total amount of emission reductions by EU ETS multinationals over the same period, $\Delta CO2_t$ [15]. As a result, we measure an indicator of leakage as the share of EU emission reductions by multinationals that can be attributed to leakage:

$$LEAK_t = \frac{\sum_{i \in ETS} l_{it}^{EU}}{\Delta CO2_t}$$

In the last row of Table 7, we report this leakage indicator for the last year of our sample, 2014, in each of our different specifications. Against this background, our analysis reveals that we cannot reject that up to 14.4% of the reductions made between 2008 and 2014 might have been the result of leakage. For the most policy-relevant subset of multinationals, the subsample of firms which report positive CO_2 emissions in the EU initially, this figure is 6.4%. We conclude that our results provide strong evidence that EU ETS-regulated multinationals achieve equally substantial global emission reductions.

[15] For internal consistency we rely on an estimate based on our sample. We discuss below how our sample relates to official data on emission reductions. We define δ as the average annual change of EU emissions by ETS multinationals over the sample period: $\delta = \frac{1}{\sum_{i \in ETS} T_i} \sum_{i \in ETS} \sum_{t \in 2008-2014} \left(CO2_{it}^{EU} - CO2_{it-1}^{EU} \right)$ where T_i is the number of years a multinational i is in the sample. We consequently estimate aggregate emission reductions over the sample period as $\Delta CO2_t = \delta \times (t - t_0) \times \#\{ETS\}$ where #{ETS is the number of ETS firms in the sample

5.3.3 Price response

In a third sensitivity analysis on the null result, we consider the spot price on the EU ETS. The central driver of emission reductions in a carbon market is the allowance price. While the EU ETS might not have had much impact on leakage in the past, it might have some as the cap is further reduced - for instance, through the market stability reserve - and therefore prices increase beyond 2008-2014 levels. Granted, the observed spot price is not necessarily the relevant price as emissions are likely highly complementary to fixed investment, which is guided by long term price expectations that could diverge. Moreover, what matters for carbon leakage is fundamentally the price difference between the EU ETS and that of the rest of the world, which depends on policy action in non-EU countries. Still, at least since EU ETS Phase II when permit banking was introduced (2008), the spot price should be indicative of the long term price expectations. Moreover, during our sample period spot prices moved considerably, from €24 per tonne of CO_2 in 2008 to only €4 in 2013. So it is reasonable to examine any potential linkage between observed prices and emissions. While €24 might still be lower than future price expectations, a sixfold change makes for a fairly wide range in which a differential response would become visible. Table 8 reports fixed effects regressions of the EU emissions share on lagged EU ETS permit spot prices [16]. In column 1, we find that the price effect is negative - as would be expected - although not significant. In column 2, we introduce a quadratic price term and find point estimates consistent, though not significant, with carbon leakage effects occurring at higher prices only. In column 3, we explore whether price effects are different for firms more exposed to low regulation regions abroad (i.e. the CLIMI index). We would expect a stronger impact of higher prices on the carbon leakage for such firms. Interestingly, we find the contrary: firms more exposed to regions with less stringent climate regulation display *less* of a carbon leakage effect. In column 4, we include controls for differential regulation exposure and for a nonlinear price

[16] For simplicity, all regressions are based on the sample of firms with non zero EU emissions in the first period we observe them - i.e. corresponding to column 3 in Table 4.We find the same broad results irrespective of the sample and these additional results are available on request.

Table 8: Regressions of EU Share on Price

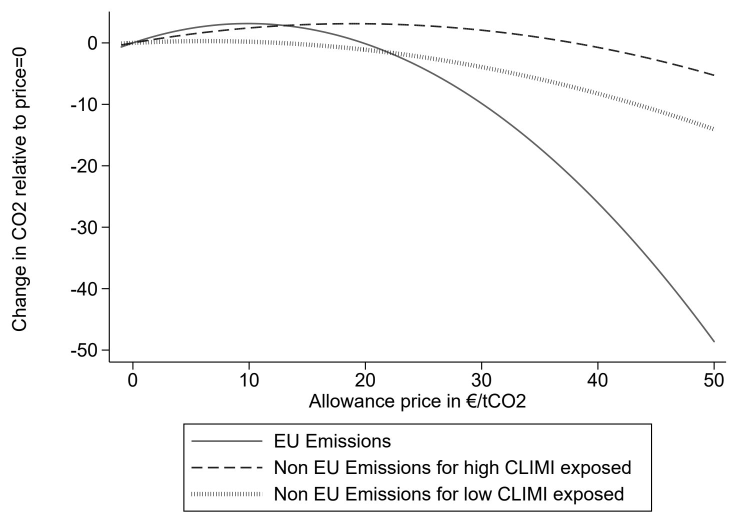
Dependent Variable	Δ Share of EU Emissions			
	(1)	(2)	(3)	(4)
$Price \times ETS$	-0.00118	0.00228	-0.00498**	-0.00383
	(-0.87)	(0.47)	(-2.62)	(-0.54)
$Price^2 \times ETS$		-0.000135		-0.0000468
		(-0.68)		(-0.16)
$Price \times ETS \times LowRegulation$			0.00736***	0.0125*
			(3.89)	(1.78)
$Price^2 \times ETS \times LowRegulation$				-0.000196
				(-0.70)
Observations	2441	2441	2441	2441
Firms	683	683	683	683

NOTES: t statistics in parentheses. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. Only firms with positive EU emissions in the first period for which the company answered the CDP survey (t=1) are included. All regressions include company fixed and time fixed effects. The price variable is lagged by one period.

response simultaneously. This indicates no carbon leakage even for multinationals that are already present in jurisdictions with low regulatory pressure on CO_2 emissions.

What could explain this result? In Table 9 we consider separately the different components of the share of emissions. This reveals that there is clear evidence of a non-linear price effect for both EU and RoW emissions, and that the CLIMI effect - i.e. a heterogeneity in the response of low regulation exposed firms - derives entirely from RoW emissions. This is consistent with the following interpretations. Firstly, this is evidence for price threshold effects: firms will only respond with carbon reductions if the price exceeds a minimum threshold, e.g. for EU emissions this would be at a carbon price of € 9.9 when the marginal price effect turns negative. Secondly, the EU ETS leads to policy leakage effects, with emissions being also reduced outside the EU at higher prices. This policy leakage effect is stronger for firms more active in low regulation countries because - presumably - marginal abatement costs are relatively lower there due to lacking existing regulations. In Figure 7 we summarise this evidence by plotting the implied carbon abatement functions. If carbon leakage as a result of the EU ETS were to occur, the non-EU emissions curves would be upward sloping in the EU ETS allowance spot price. However, the data indicate the opposite: all curves are downward sloping, implying that higher carbon prices in the EU ETS are associated with fewer emissions both in the EU and abroad. However, the magnitude of the response differs: as is to be expected, domestic EU emissions respond the most. RoW emissions in firms primarily active in low regulation countries and RoW emissions for firms in high regulation regions respond slower, and only at higher price levels.

Figure 7: The counterfactual carbon response to the EU ETS allowance price



Note: The figure visualizes the quadratic price response functions estimated in Table 9

On balance, the three different extensions appear to confirm our main null result that the EU ETS has not led to carbon leakage within multinational firms.

Table 9: Regressions of Emissions on ETS Price

	(1)	(2)	(3)	(4)
Dependent Variable		Δ Emissions EU		
$Price \times ETS$	-0.188	0.637*	-0.0730	0.603**
	(-1.47)	(1.87)	(-1.14)	(2.62)
$Price^2 \times ETS$		-0.0322*		-0.0266**
		(-1.79)		(-2.71)
$Price \times ETS \times LowRegulation$			-0.222	0.0506
			(-0.92)	(0.08)
$Price^2 \times ETS \times LowRegulation$				-0.0102
				(-0.32)
Minimum Price for Reductions		9.895		8.892
Dependent Variable		Δ Emissions RoW		
$Price \times ETS$	0.00128	0.218*	0.108*	0.330**
	(0.02)	(1.76)	(1.74)	(2.07)
$Price^2 \times ETS$		-0.00844		-0.00871*
		(-1.55)		(-1.71)
$Price \times ETS \times LowRegulation$			-0.206**	-0.236
			(-2.14)	(-1.10)
$Price^2 \times ETS \times LowRegulation$				0.00119
				(0.13)
Minimum Price for Reductions		12.89		6.289
Dependent Variable		Δ Emissions Global		
$Price \times ETS$	-0.186	0.854**	0.0348	0.933**
	(-1.11)	(2.05)	(0.33)	(2.82)
$Price^2 \times ETS$		-0.0406*		-0.0353**
		(-1.85)		(-2.76)
$Price \times ETS \times LowRegulation$			-0.428	-0.185
			(-1.34)	(-0.24)
$Price^2 \times ETS \times LowRegulation$				-0.00896
				(-0.23)
Minimum Price for Reductions		10.52		8.450
Observations	2441	2441	2441	2441

NOTES: t statistics in parentheses. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. Only firms with positive EU emissions in the first period for which the company answered the CDP survey (t=1) are included. All regressions include company fixed and time fixed effects. The price variable is lagged by one period.

6 Conclusion

This paper uses a unique dataset on within-firm carbon emissions to study the distribution of carbon emissions of multinational firms across countries and over time. We focus on the concern that EU climate policy, particularly its flagship EU Emissions Trading System, could lead to carbon leakage, i.e. firms could re-locate polluting activities to non-EU locations in response to being subjected to the EU ETS. Using both exploratory data analysis and regression analysis, and looking at a wide range of sub-samples and specifications, we cannot find any evidence for carbon leakage in our data. Our estimation strategy cannot necessarily reveal the causal effect of the EU ETS on leakage, as we cannot rule out that region-specific productivity shocks might confound the effects of the EU ETS. However, our results suggest that carbon leakage due to the EU ETS is unlikely to have been an economically meaningful concern until 2014.

Why are the effects of the EU ETS on carbon leakage so small that they cannot so far be statistically detected? The evidence presented here is based on multinational companies that would be expected to be the first to react to unilateral climate change regulations by shifting production and emissions to less-regulated jurisdictions. A first possibility is that the EU ETS, by widely allocating emission permits to carbon-intensive and trade-exposed industries for free, is successfully preventing leakage effects. Indeed, Martin et al. (2014a) argue that the European Commission has been handing out free permits more generously than necessary. A second possibility is that the statistically insignificant effects identified thus far simply reflect the lack of stringency of the EU ETS. The price of carbon in the European market has fluctuated between 0 and 30 euros per tonne since its introduction, spending most of the time in the lower range of this interval. While regulation that does not lead to carbon leakage should be favored, it is likely that the threats posed by climate change will require more stringent regulations going forward than the EU ETS experience analyzed here, and therefore more likely to lead to leakage. However, the regulatory gap could also narrow in the future with emerging economies such as China implementing more stringent climate policy. At present, we can conclude that modest differences in climate policy stringency across countries do not seem to induce carbon leakage, even among multinational companies which can easily shift production and emissions across jurisdictions. An important question for future research is to understand how large these differences can be before carbon leakage starts becoming an issue (and in which sectors), and how climate policies should be adjusted as other countries' regulations evolve.

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Appendix

A Merging of datasets

The challenge of the data merging exercise lies in matching EU ETS *installations* to *multinational companies*. For some countries in our sample, the company registration numbers of the installation operators were obtained directly, either from national emissions trading registries or from the European Union Transaction Log (EUTL), the EU body to which national registries report. For the other countries, a combination of exact and approximate text matching methods were used to establish a link between firm data and regulatory data. This was complemented by further manual searches, and extensive manual double-checking. The most consistent way to then perform the matching from installations to multinationals is to use the Bureau van Dijk company identifier, which we construct for the CDP data using the ORBIS database. In some cases, the CDP raw data provides the Bureau van Dijk identifier, while in others it will provide the ISIN number that is also a search criteria in the ORBIS dataset. In other instances we had to resort to manual name matching. Once we had identifiers for all multinationals in the CDP data, here are the steps we perform for the EU ETS treatment coding.

1. Find subsidiaries: For each of the multinationals, we extract in ORBIS a list of its subsidiaries. For each subsidiary, we extract the share that the parent multinational owns in the subsidiary. The number of subsidiaries for each multinational is capped at 1000 due to computational constraints. To transform verbal information from the ORBIS database into percentages, we replace 'wholly owned' with 100%, and majority-owned by 50.01% (as suggested by Kalemli-Ozcan et al. (2019)). If a firm's shares are listed as exceeding a percentage of a given size, we code it as that percentage plus 0.01 percentage points, and likewise for shares listed as being lower than a certain percentage. For example, an entry of '>50%' is coded as '50.01%'. The observations that contained 'PG' and 'NG' could not be given an unambiguous quantitative meaning and are thus coded as missing. This concerns only few subsidiaries of a limited number of multinational firms.

2. Keep subsidiaries for whom the multinational owns at least 20% of the shares: Based on the distribution of the ownership share of the multinationals in their subsidiaries, we select 20% as the threshold below which we drop a subsidiary. The reasoning for this choice is data-driven: the distribution of the percentage of all shares in a subsidiary held by a multinational shows three clear peaks. At 100%, at 50.01%, and close to 0%. We think it reasonable to consider a parent company as treated if its ownership of an EU ETS subsidiary is substantial, which includes the first two peaks but not the last. To not make the cutoff too conservative at 50.01%, we include all subsidiaries that are owned with at least 20%. Note, however, that a change in this threshold would not meaningfully impact the results due to the tiny number of subsidiaries (2.5%) that are owned with an ownership share between 20% and 50%.

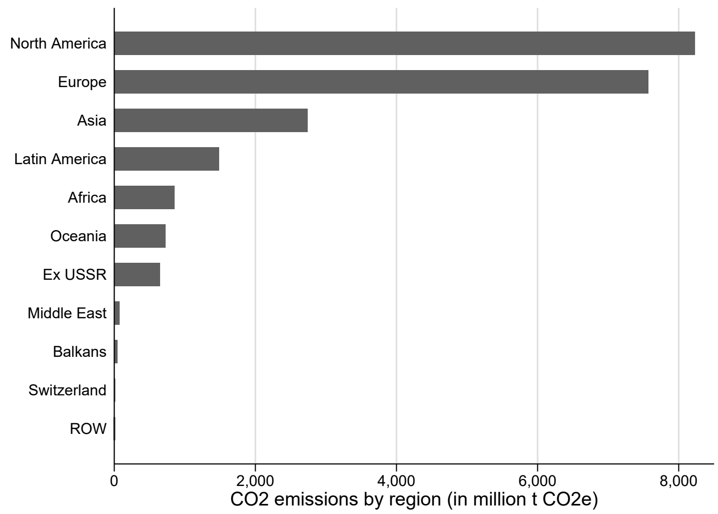
3. Merge to EUTL database: We then merge the dataset of remaining subsidiaries as well as the parent multinationals to the EUTL database of all EU ETS-regulated installations. We do this in a two-step procedure, matching first the subsidiaries and then the multinationals themselves to the EUTL database based on the Bureau van Dijk identifier in ORBIS. Additionally, we manually check for consistency of the merge. A multinational is then defined as treated by the EU ETS if at least one of its subsidaries or the multinational itself owns an installation included in the EU ETS. In other words, we code a CDP firm as treated if it controls more than 20% of any EU ETS installation. Overall, 261 multinationals are treated in our sample.[1]

[1]We believe that the way we code EU ETS multinationals is the most reasonable way of doing so: it is the most transparent, and it allows for a clear selection of which subsidiary is a significant enough subsidiary to induce the parent company to be considered as treated by the EU ETS. It is possible, however, to redo the treatment coding in reversed order. That is, we can first match all EU ETS installations from the EUTL to ORBIS, and then look up their parent companies. We have found this merge to be less transparent and clean, and found that the number of EU ETS treated firms differs greatly depending on the level of ownership considered (owning company or immediate shareholder, domestic ultimate owner and global ultimate owner). Also, in contrast to our preferred way of coding the treatment status, this method does not allow to use information on the intensity of ownership, i.e. the percent of all shares of a subsidiary owned by a parent company. In the limit, this method therefore risks coding a CDP multinational as treated when one of their subsidiaries owns a minuscule share of an EUTL installation. Our results, however, are robust to coding CDP firms as treated in this manner.

B Additional descriptive statistics

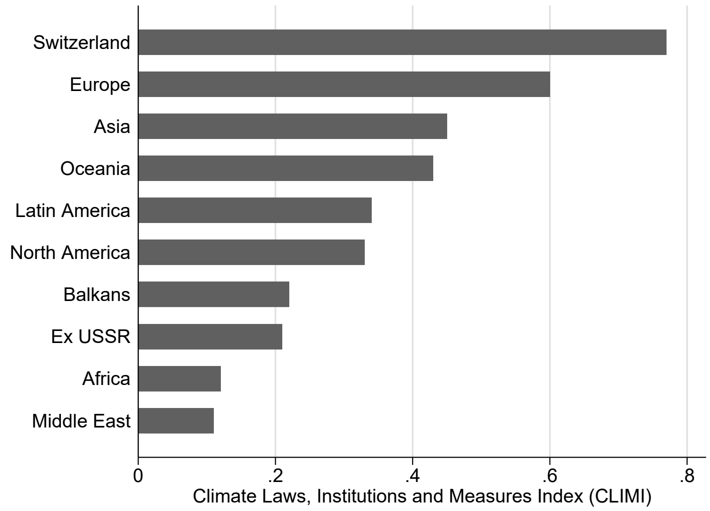
In this section, we present additional features of the dataset. We firstly show the geographical spread of emissions reported in the CDP database for multinationals that are active in Europe in Figure B.1: North America and Europe dominate, followed by Asia, Latin America and Africa. Relatively limited activity in terms of emissions data is reported for the Middle East.

Figure B.1: Geographical spread of CO_2 emissions



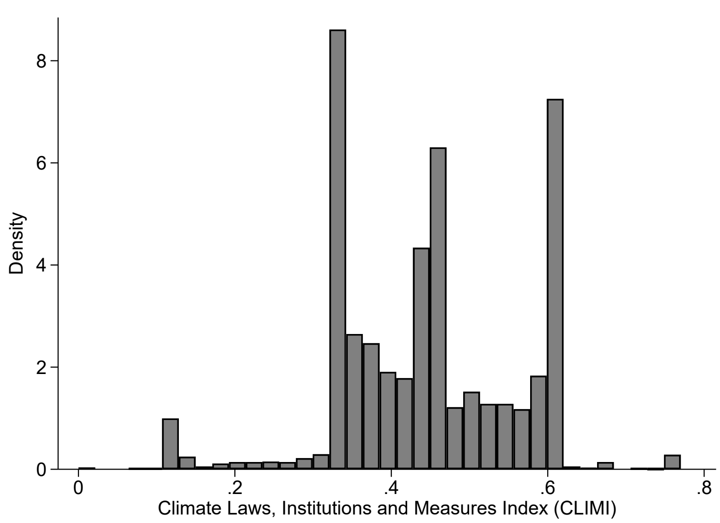
The raw stringency of climate policy across regions based on the Climate Laws, Institutions, and Measures Index (CLIMI) varies as shown in Figure B.2. Europe's climate policy stringency dominates that of all other countries with the notable exception of Switzerland (which has since linked its own emissions trading system to the EU ETS). Climate policy is relatively more loose in the Middle East and in Africa.

Figure B.2: Stringency of climate policy across regions



The resulting variation in policy stringency faced by multinational firms in our sample, weighted by each firm's geographical spread of emissions on a by year-basis, is shown in Figure B.3. The resulting variation is spread across the range from 0 to 0.8, with a notable mass of firm-year observations between 0.3 and 0.65.

Figure B.3: Emissions-weighted stringency of climate regulation at the multinational firm-year level



C A simple model of carbon leakage

This sections introduces a simple model to study within-firm leakage in more detail. We consider multinational firms that produce a final good Q. To produce Q, firms can invest capital K_R in two regions $R \in \{EU, RoW\}$. Capital inputs translate into final output according to a CES production function:

$$Q = \left[(A_{EU} K_{EU})^{\frac{\gamma-1}{\gamma}} + (A_{RoW} K_{RoW})^{\frac{\gamma-1}{\gamma}} \right]^{\frac{\gamma}{\gamma-1}}$$

where γ is the elasticity of substitution between EU and RoW emissions and A_{EU} and A_{RoW} are region specific productivity shocks. Suppose that emissions are a linear function of capital: $CO2_R = \rho_R K_R$ for $R \in \{EU, RoW\}$. For simplicity suppose that capital costs r are uniform across regions. However, there is a charge τ_{EU} for emitting carbon in the EU and an even higher charge τ_{ETS} for ETS regulated firms. For a given quantity of output Q, cost minimization implies the following cost function:

$$C(Q, r, \tau) = Qc(r, \tau) = Q \left[\left(\frac{\rho\tau + r}{A_{EU}} \right)^{1-\gamma} + \left(\frac{r}{A_{RoW}} \right)^{1-\gamma} \right]^{\frac{1}{1-\gamma}}$$

where we assume for simplicity that firms always invest in both locations.

Emissions in each location are then given by:

$$CO2_{EU} = \rho_{EU} Q A_{EU}^{\gamma-1} \left(\frac{\rho_{EU}\tau + r}{c(r, \tau)} \right)^{-\gamma}$$

$$CO2_{RoW} = \rho_{RoW} Q A_{RoW}^{\gamma-1} \left(\frac{r}{c(r, \tau)} \right)^{-\gamma}$$

Final output demand is described by a simple log linear form:

$$Q = \Lambda^{\eta-1} P^{-\eta}$$

where Λ is a firms specific demand shock. Profit maximization implies markup pricing

$$P = \mu c\left(r, \tau\right)$$

where $\mu = \frac{1}{1-\frac{1}{\eta}}$

Equilibrium output is consequently determined by

$$Q = \Lambda^{\eta-1}\left(\mu c\left(r, \tau\right)\right)^{-\eta}$$

Hence:

$$CO2_{EU} = \rho\Lambda^{\eta-1}\mu^{-\eta}c\left(r, \tau\right)^{\gamma-\eta} A_{EU}^{\gamma-1}\left(r + \rho\tau\right)^{-\gamma}$$

$$CO2_{RoW} = \rho\Lambda^{\eta-1}\mu^{-\eta}c\left(r, \tau\right)^{\gamma-\eta} A_{RoW}^{\gamma-1}r^{-\gamma}$$

We can also derive a firm's global profit as

$$\Pi = QP - Qc(r, \tau) = Q(\mu - 1)c(r, \tau) = \Lambda^{\eta-1}\frac{\mu - 1}{\mu^{\eta}}c(r, \tau)^{1-\eta}$$

We are now in a position to precisely define carbon leakage from the EU. We can measure the extent of carbon leakage by the change of RoW emissions by a multinational company due to an increase of CO_2 pricing in the EU

$$\Delta CO2_{RoW}^{Leak} = \frac{\partial CO2_{RoW}}{\partial\tau}\Delta\tau$$

Looking at equation C.1 we see that leakage can be positive (which represents carbon leakage) or indeed negative; i.e. RoW emissions reduce because of EU policy. The sign will depend on the relative size of the elasticity of substitution γ and the price elasticity of demand η. An increase in tax τ will always lead to an increase in unit costs $c(r, \tau)$. This will lead to an increase in RoW CO_2 emissions if $\gamma > \eta$. Put differently, leakage will be negative if EU and RoW capital are highly complementary ($\gamma \to 0$), or if the demand for a firm's output is highly inelastic ($\eta \to \infty$). There is at least one further mechanism that is relevant for leakage effects, particularly in the context of multinational firms: investments in abatement effort that can lead to technology spillovers. Such investments could include both investments in tangible capital that reduces pollution or indeed intangible capital such as research on how to reduce a company's carbon footprint. We can capture this phenomenon by defining the pollution intensity of capital in the EU as follows:

$$\rho_{EU} = \phi_0 \frac{1}{1 + e_E U}$$

where e is the abatement effort. We also assume that

$$\rho_{RoW} = \phi_0 \frac{1}{1 + \phi e_E U}$$

which allows for effort undertaken in the EU to spill over to a multinational firm's operations in other jurisdictions, with ϕ representing the degree of spillover. Suppose that one unit of abatement effort comes at a cost δ. Firms will determine the amount of effort by maximizing

$$\Pi(\rho_{EU}(e)) - e\delta$$

This leads to the first order condition

$$\frac{\partial \Pi}{\partial e} \leq \delta$$

which will hold with equality for $e > 0$. Note that

$$\frac{\partial \Pi}{\partial e} = \Lambda^{\eta-1} \frac{\mu - 1}{\mu^{\eta}} (1 - \eta) c(r, \tau, \rho)^{-\eta} \frac{\partial c(r, \tau, \rho)}{\partial \rho} \frac{\partial \rho}{\partial e}$$

$$= \Lambda^{\eta-1}\frac{\mu-1}{\mu^{\eta}}(\eta-1)c(r,\tau,\rho)^{-\eta}\frac{\partial c(r,\tau,\rho)}{\partial\rho}\frac{1}{(1+e)^2}$$

$$= \frac{\Lambda^{\eta-1}}{\mu^{\eta}}c(r,\tau,\rho)^{-\eta}\frac{\partial c(r,\tau,\rho)}{\partial\rho}\frac{1}{(1+e)^2}$$

where the last equality follows from $\frac{\mu-1}{\mu^{\eta}}(\eta-1) = \mu^{-\eta}$. Further note that

$$\frac{\partial c(r,\tau,\rho)}{\partial\rho} = c(r,\tau,\rho)^{\gamma}\left(\frac{\rho\tau+r}{A_{EU}}\right)^{-\gamma}\frac{\tau}{A_{EU}}$$

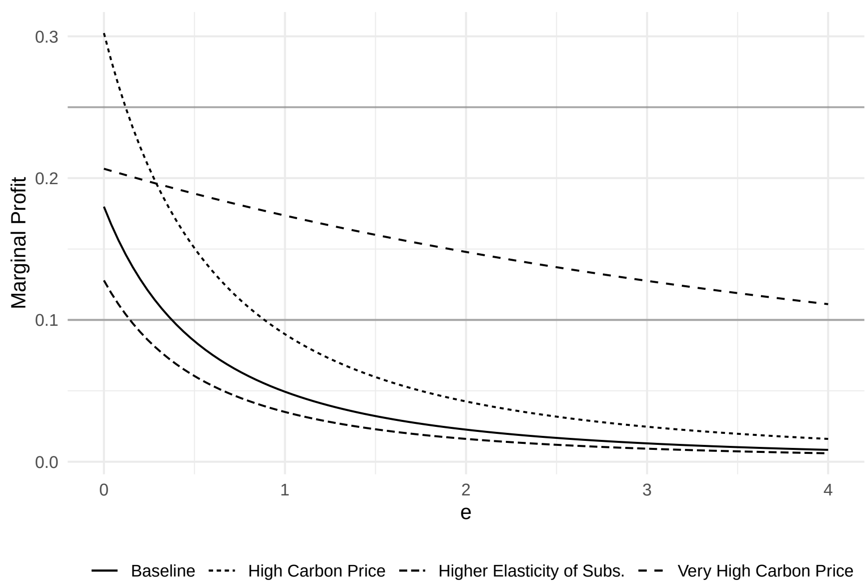
Hence the first order condition becomes

$$\frac{\partial\Pi}{\partial e} = \frac{\Lambda^{\eta-1}}{\mu^{\eta}}c(r,\tau,\rho)^{\gamma-\eta}\left(\frac{\rho\tau+r}{A_{EU}}\right)^{-\gamma}\frac{\tau}{A_{EU}}\frac{1}{(1+e)^2} \leq \delta$$

Given that marginal profits are downward sloping in e, a solution always exists. Figure C.1 illustrates a number of cases. In the baseline we consider a case with $\gamma = 2.25$ and $\eta = 2$. If the elasticity of substitution increases (e.g. to 4.25) the marginal profit line moves left implying a lower level of abatement all else equal: firms will find it easier to substitute emissions abroad rather than engage in more abatement efforts. If we increase the carbon price, the marginal profit line moves rightwards leading to more abatement effort initially. However, an increase in the carbon price also tilts the curve, which at some point leads to a reduction in abatement effort and eventually to no abatement effort at all: if carbon prices are so high that firms shift most of their production abroad, there is little incentive to invest in abatement.

This dynamic leads to an inverted U-shaped curve for the relationship between carbon prices and abatement effort as illustrated in Figure C.2 panel (a). The model also implies a minimum price threshold for companies to engage in any abatement effort. As a result, there is an optimal range for carbon prices as far as abatement effort is concerned. Looking at RoW emissions in Panel (b), we see that, as a consequence of the interaction between spillovers and outsourcing of production, emissions will initially go up, then down, and then up again

Figure C.1: Marginal Profits for different parameter values

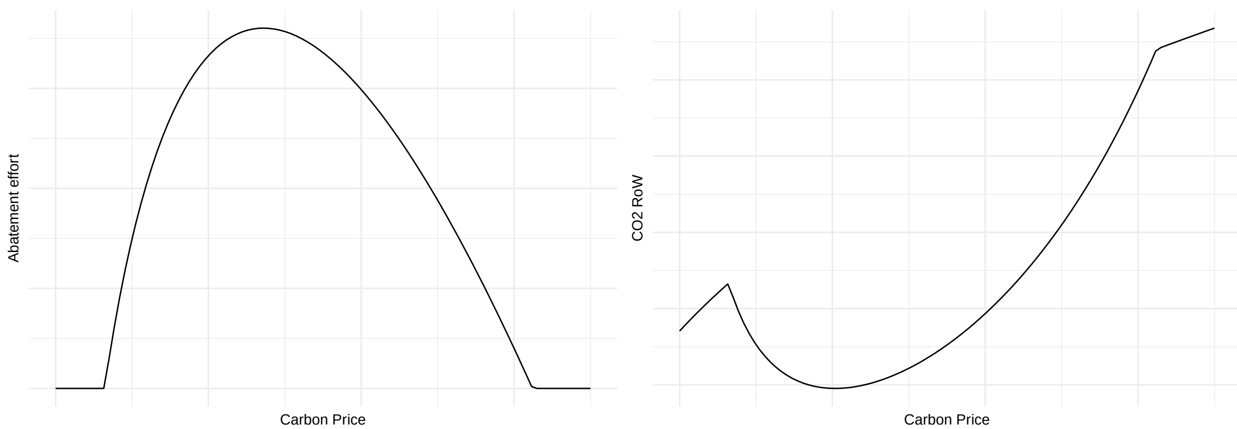


Notes: Visualisation of profit equation for various parameter assumptions.

as the EU carbon price increases. We analyse this question empirically in an extension of our empirical framework in section 5.3.3.

Figure C.2: Abatement and RoW emissions for different carbon prices

(a) Abatement Effort (b) RoW Emissions



Notes: Visualisations of the optimal amount of abatement effort and RoW emissions for different levels of EU carbon prices from simulations. Elasticity of substitution $\gamma = 2.25$. Elasticity of demand $\eta = 2$

D Further robustness estimations

We have conducted a number of variations of the analysis reported in Table D.1 for robustness purposes. First, we use the sample of firms as in column (2) of Table 4 and we repeat the estimation of equation 3 including logged control variables such as capital stock, turnover and the number of employees. Column (1) of Table D.1 shows that our main results are not altered by the inclusion of control variables. Results are also not altered when failing to control for the number of years since the last report - $timestep_{it}$ in equation 3 (column 2). In column (3) we consider only year-on-year changes in carbon emissions and remove observations where the number of years since the last report is greater than 1. None of these robustness checks alter our finding of the absence of a leakage effect due to the EU ETS.

Table D.1: Regressions of the share of emissions in EU - Robustness

Dependent variable:	Δ Share of EU emissions		
Sample composition: EU>0 + RoW>0 in some year	(1)	(2)	(3)
Panel A: All Firms			
ETS	-0.00697	-0.00665	-0.0120*
	(-1.07)	(-1.03)	(-1.83)
ln (Revenue)	0.0140**	0.0141**	0.0150**
	(2.39)	(2.40)	(2.46)
ln (Assets)	-0.00650	-0.00640	-0.00803*
	(-1.49)	(-1.46)	(-1.83)
ln (Employment)	-0.00306	-0.00311	-0.00456*
	(-1.17)	(-1.19)	(-1.65)
Observations	2393	2393	2275
Number of firms	676	676	664
R^2	0.0140	0.00769	0.00836
Panel B: Manufacturing Firms			
ETS	-0.00432	-0.00453	-0.0127
	(-0.53)	(-0.56)	(-1.55)
ln (Revenue)	0.0244	0.0243	0.0287*
	(1.54)	(1.52)	(1.78)
ln (Assets)	-0.0183	-0.0182	-0.0206
	(-1.35)	(-1.34)	(-1.53)
ln (Employment)	0.000326	0.000601	-0.00187
	(0.07)	(0.13)	(-0.40)
Observations	1433	1433	1356
Number of firms	388	388	380
R^2	0.0158	0.00747	0.0103
Panel C: Manufacturing Firms at Risk of Carbon Leakage			
ETS	0.000570	0.000217	-0.0125
	(0.06)	(0.02)	(-1.16)
ln (Revenue)	0.0174	0.0174	0.0309*
	(1.09)	(1.08)	(1.88)
ln (Assets)	-0.0100	-0.00982	-0.0140
	(-0.85)	(-0.83)	(-1.29)
ln (Employment)	-0.00486	-0.00503	-0.0110*
	(-0.85)	(-0.87)	(-1.86)
Observations	793	793	745
Number of firms	220	220	214
R^2	0.0111	0.00840	0.0100
Control for length of Δ	YES	NO	Δ=1 year

NOTES: t statistics in parentheses. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01. Only firms that have positive emissions in both EU and RoW in some year are included. Column 1 is equivalent to Table 4's column 2 but adds controls for logged revenue, assets and employment obtained from balance sheet data. Column 2 does not control for the number of years since the last observation and column 3 only includes observations where the Δ Share of EU emissions is for one year.

E List of sectors judged at risk of carbon leakage

The following table lists all sectors that are coded at risk of carbon leakage (as detailed in Section 3). The number refers to the NACE Rev. 2 classification (Core Code, 4 Digits).

510 Mining of hard coal
610 Extraction of crude petroleum
710 Mining or iron ores
729 Mining of other non-ferrous metal ores
811 Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate
899 Other mining and quarrying n.e.c.
910 Support activities for petroleum and natural gas extraction
1081 Manufacture of sugar
1089 Manufacture of other food products n.e.c.
1101 Distilling, rectifying and blending of spirits
1102 Manufacture of wine from grape
1310 Preparation and spinning of textile fibre
1393 Manufacture of carpets and rugs
1413 Manufacture of other outerwear
1414 Manufacture of underwear
1520 Manufacture of footwear
1610 Sawmilling and planing of wood
1711 Manufacture of pulp
1712 Manufacture of paper and paperboard
1722 Manufacture of household and sanitary goods and of toilet requisites
1724 Manufacture of wallpaper
1729 Manufacture of other articles of paper and paperboard
1920 Manufacture of refined petroleum products
2012 Manufacture of dyes and pigments
2013 Manufacture of other inorganic basic chemicals
2014 Manufacture of other organic basic chemicals
2015 Manufacture of fertilisers and nitrogen compounds
2017 Manufacture of synthetic rubber in primary forms
2020 Manufacture of pesticides and other agrochemical products
2042 Manufacture of perfumes and toilet preparations
2059 Manufacture of other chemical products n.e.c.
2060 Manufacture of man-made fibres
2110 Manufacture of basic pharmaceutical products
2120 Manufacture of pharmaceutical preparations
2211 Manufacture of rubber tyres and tubes; retreading and rebuilding of rubber tyres
2219 Manufacture of other rubber products
2229 Manufacture of other plastic products
2311 Manufacture of flat glass
2319 Manufacture and processing of other glass, including technical glassware
2342 Manufacture of ceramic sanitary fixtures

2351 Manufacture of cement
2391 Production of abrasive products 2
2410 Manufacture of basic iron and steel and of ferro-alloys
2420 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel
2441 Precious metals production
2442 Aluminium production
2444 Copper production
2573 Manufacture of tools
2593 Manufacture of wire products, chain and springs
2599 Manufacture of other fabricated metal products n.e.c.
2611 Manufacture of electronic components
2612 Manufacture of loaded electronic boards
2620 Manufacture of computers and peripheral equipment
2630 Manufacture of communication equipment
2640 Manufacture of consumer electronics
2651 Manufacture of instruments and appliances for measuring, testing and navigation
2652 Manufacture of watches and clocks
2660 Manufacture of irradiation, electromedical and electrotherapeutic equipment
2670 Manufacture of optical instruments and photographic equipment
2711 Manufacture of electric motors, generators and transformers
2712 Manufacture of electricity distribution and control apparatus
2740 Manufacture of electric lighting equipment
2751 Manufacture of electric domestic appliances
2790 Manufacture of other electrical equipment
2811 Manufacture of engines and turbines, except aircraft, vehicle and cycle engines
2813 Manufacture of other pumps and compressors
2814 Manufacture of other taps and valves
2815 Manufacture of bearings, gears, gearing and driving elements
2822 Manufacture of lifting and handling equipment
2823 Manufacture of office machinery and equipment (except computers and peripheral equipment)
2824 Manufacture of power-driven hand tools
2825 Manufacture of non-domestic cooling and ventilation equipment
2829 Manufacture of other general purpose machinery n.e.c.
2830 Manufacture of agricultural and forestry machinery
2891 Manufacture of machinery for metallurgy
2892 Manufacture of machinery for mining, quarrying and construction
2895 Manufacture of machinery for paper and paperboard production
2899 Manufacture of other special purpose machinery n.e.c.
3011 Building of ships and floating structures
3030 Manufacture of air and spacecraft and related machinery
3091 Manufacture of motorcycles
3099 Manufacture of other transport equipment n.e.c.
3101 Manufacture of office and shop furniture
3212 Manufacture of jewellery and related articles

3220 Manufacture of musical instruments
3230 Manufacture of sports goods
3240 Manufacture of games and toys
3250 Manufacture of medical and dental instruments and supplies
3299 Other manufacturing n.e.c.
5222 Service activities incidental to water transportation
5819 Other publishing activities
6209 Other information technology and computer service activities