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Searching for carbon leaks in multinational companies*

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Abstract

Does climate change policy cause companies to shift the location of production, thereby creating carbon leakage? We examine the impact of the European Union Emissions Trading System (EU ETS) on the geographical distribution of carbon emissions within multinational companies based on data from the Carbon Disclosure Project for the period 2007-2014. Because they already operate from multiple locations, multinational firms should be the most prone to carbon leakage. Our data includes regional emissions of 1785 companies, of which 142 are subject to EU ETS regulation. We find no evidence that the EU ETS has induced a displacement of carbon emissions from Europe towards the rest of the world. Our results suggest that claims that the EU ETS would cause carbon leakage might have been exaggerated.

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1 Introduction

With the implementation of the European Union Emissions Trading System (EU ETS) and a range of other policies, mostly supporting the deployment of renewable energy technologies, the EU 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 for carbon and energy intensive industries. Indeed, in a free-trade world, increased carbon prices following adoption of unilateral climate policies may generate a pollution-haven effect in other countries or regions, whereby foreign countries specialise in the production of carbon-intensive products in which they have a newly acquired competitive advantage and which they can subsequently export back to "virtuous" countries. If the result of climate policy is a relocation of economic activity to less-regulated regions, then the policy is not only ineffective from a climate change point of view (as emissions are likely relocating with production, rather than reducing) but also costly from an economic point of view, by destroying jobs and economic activity in environmentally-friendly 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.

In this paper we explore this hypothesis using a unique sample of panel data on carbon emissions for 1785 multinational companies. Multinational companies with operations across a wide range of jurisdictions might be particularly prone to react to regulation that imposes higher costs in some locations by shifting production to less regulated regions. 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 view to understanding the exposure of companies to future climate change policies. The unique feature of the CDP data is that emissions for multinational businesses are broken down by country. Hence we can study whether multinationals subject to the European Union Emissions Trading System (EU ETS) reduce emissions in one location only to increase them elsewhere. Specifically, we compare emissions in Europe with emissions occuring outside Europe within the same company between 2007 and 2014. On the basis of this data, we do not find any evidence that the EU ETS caused leakage of carbon out of Europe. This conclusion does not only emerge for the average firm in our sample but also for various sub-samples, including -

most importantly - 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.

This paper relates to the vast literature that seeks to estimate the impact of unilateral climate change policies on carbon leakage (see Sato and Dechezleprêtre (Forthcoming) and Dechezleprêtre and Sato (Forthcoming) for recent reviews)[1]. This literature has so far mainly used ex-ante model simulation strategies to assess the quantitative impacts of unilateral climate change policy, typically using Computable General Equilibrium (CGE) models (see Carbone and Rivers, 2014, for a recent review of this literature). These studies have estimated a wide range of leakage rates associated to different emission reduction targets under the Kyoto Protocol. Dröge et al. (2009) reports rates between 5 and 25%, while Lanz and Rausch (2011) find central estimates in the range of 15–30%. However, some studies find negative leakage rates due to spillover effects (e.g. Barker et al. (2007)) while some others report leakage rates above 100% implying that emission reduction efforts in one region are more than compensated by increased emissions in other regions, for example because production shifts to less-technologically advanced (and thus more carbon-intensive) regions. In the context of the EU ETS, partial equilibrium models have also been used, observing sectoral differences in carbon leakage rates due to differences in carbon intensity of production, abatement potential, transport costs, product differentiation and other parameters. Generally the steel sector, characterized by both high product differentiation and abatement potential, has been found to experience higher leakage rates (see Sato (2013)). Overall, these results are very sensitive to model assumptions and are suggestive of a large uncertainty, highlighting the need for empirical studies to better identify the magnitude of the effect of climate change regulation on carbon leakage. In comparison to CGE models, however, there are still few empirical contributions to this subject. Aichele and Felbermayr (2012) and Aichele and Felbermayr (2011) analyse the impact of carbon emissions reduction commitments taken under the Kyoto Protocol on carbon leakage and find statistically significant and large effects. In the former paper, the authors find that the Kyoto commitment is associated with an increase in the ratio of imported embodied carbon emissions over domestic emissions by about 14%. Using a matching technique, the latter paper finds that exports by Kyoto countries are reduced by 13% to 14% following the signing of the protocol. Gerlagh and

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

Mathys (2011) also provide empirical evidence supporting the carbon leakage effect. Using a panel of 14 high income countries over 28 years, they analyze the impact of energy abundance on country net exports and find that energy abundant countries have a higher level of energy embodied in exports relative to imports.

A few recent studies have begun to investigate the impact of the EU ETS on carbon leakage. Martin et al. (2013b) review the ex-post empirical evidence of the impact of the EU ETS on carbon leakage. Although the studies outcomes differ across papers, there is overall no indication that the EU ETS had any strong negative effects on the economic performance of regulated firms and that it has led to carbon leakage. Using installation level data for french manufacturing firms (Wagner et al., 2013) find a significant negative impact on on employment of ETS regulated facilities. However, it is not clear that this associated with leakage. The facility level data allows them to examine leakage between ETS and non ETS facilities of firms that control both types of facilities. This does not lead to any evidence for leakage however.. A negative employment impact arises in a cross-country study, in particular in the non-metallic minerals industry (Abrell et al., 2011), suggesting that production might have shifted as a consequence of the EU ETS. In contrast, German manufacturing firms show no significant reduction in employment and turnover as a result of the EU ETS (Wagner et al., 2014). This is in line with sector-level evidence showing that firms' market power allows them to pass through the cost increases induced by carbon trading on to product prices (De Bruyn et al., 2008). Finally, Martin et al. (2013a) survey close to 800 manufacturing firms in six EU countries. Firms regulated under the EU ETS report a higher propensity to downsize their operations in response to future carbon pricing than non-EU ETS firms, but the overall effect is small and concentrated in a few sectors.

Our paper contributes to this literature by providing new evidence on the link between EU ETS regulation and carbon leakage. Thanks to the data collected by the Carbon Disclosure Project (CDP), we are able to track firm level CO_2 emissions 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 the trend in CO_2 emissions of EU ETS regulated firms in European relative to non European countries.

The rest of the paper is structured as follows. The next section presents the different datasets used, in particular that obtained from CDP. Section 3 describes the method adopted for the data analysis and section 4 presents the results. Section 5 concludes.

2 Data and descriptive statistics

We construct an unbalanced panel of firms for the period 2007-2014 by combining different data sources. The data on annual firm level carbon emissions come from the Carbon Disclosure Project (CDP), an NGO acting on behalf of over 600 institutional investors which every year since 2003 have asked listed companies to disclose information on carbon emissions.[2] We obtain data on turnover, assets, number of employees and sector of activity of these companies from ORBIS, one of the largest global financial firm level database provided by Bureau Van Dijk under a commercial license. Finally, we use the European Union Transaction Log to identify companies owning at least one installation regulated under the EU ETS. [3]

As shown in Figure 1, the number of observations in the CDP grows in the intial years of our sample, and then remains above 600 throughout. The sample is constituted of 1785 companies, 142 of which are regulated under the EU ETS and 1643 companies are not regulated.

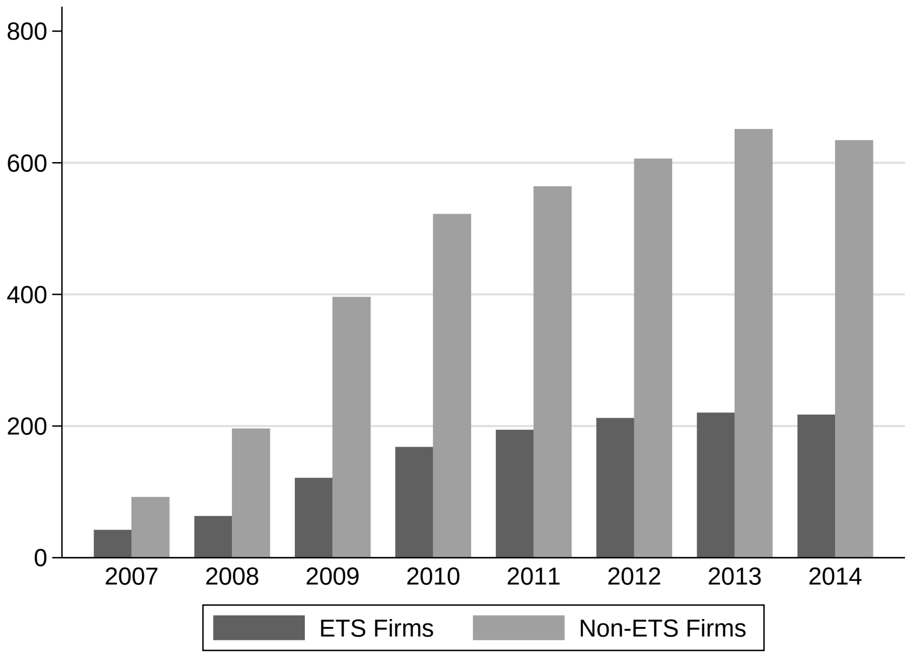
Figure 2 displays the sectoral distribution of the companies in our sample. The firms we observe are the ones who voluntarily answer the CDP questionnaire so they represent a subset of listed firms. The majority of these companies comes from the manufacturing sector. The sample also includes a large number of companies operating in the banking and financial sector, ICT companies, and utilities.

In Figure 3 we show the distribution of companies, focusing only on sectors where ETS firms operate. This subsample contains a total of 977 companies, of which 78 are regulated by the EU ETS. As expected, the majority of ETS companies in the sample operate in the manufacturing, mining and quarrying, and utilities sectors.

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

[3]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. Even with these numbers, the coding of which company is regulated by the EU ETS is not straightforward because of the challenge to assign EUTL installations to CDP companies. See Appendix B: Coding Companies as Treated by the EU ETS for details.

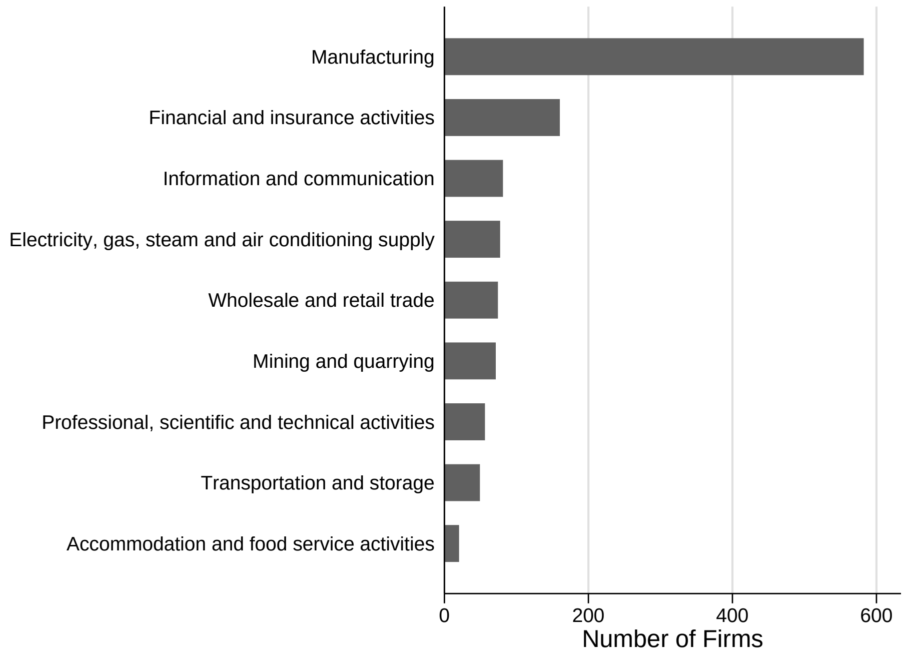
Figure 1: Number of Observations over the Period 2007-2014.



With non mandatory participation in the CDP carbon reporting program and a focus on listed companies, concerns of selection bias might arise. 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. (2011)) have shown that companies operating in cleaner sectors are more likely to report their environmental activity. This is also true of 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 as 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. 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. Our results are based on data that includes either type of firm.

Besides, there are some concerns about the consistency of survey quality across firms and over time and the lack of verification of survey answers. However, for the purpose of this study, these issues are only of concern if they vary systematically between ETS and non ETS firms.

Figure 2: Distribution of Companies Across Industry Sectors



3 Methods

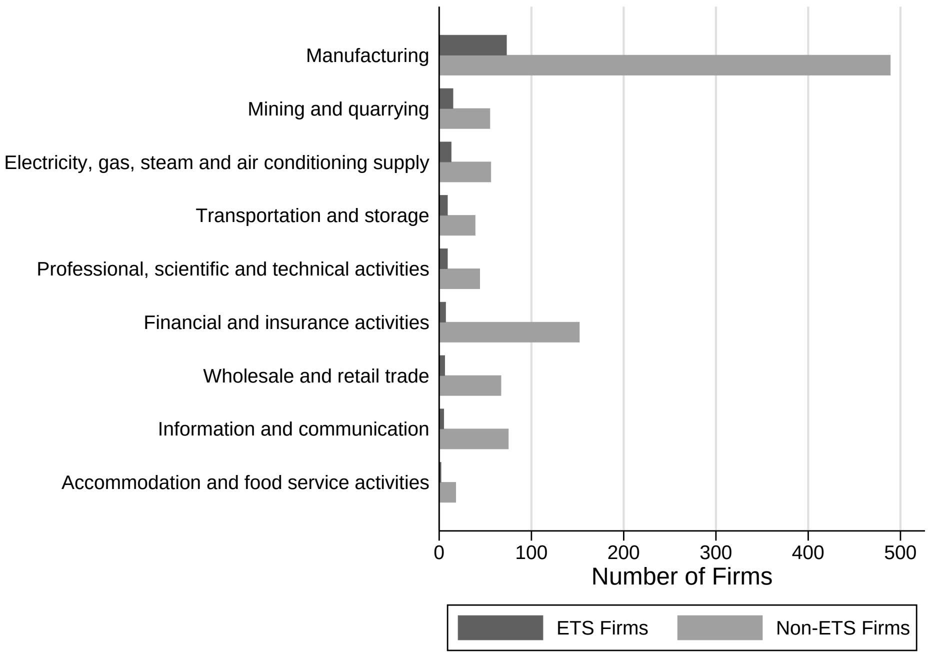
There is a range of potential definitions and types of carbon leakage, although the basic assumption behind leakage is that international trade acts as a channel by which emissions move from regulated to non-regulated entities. The main contribution of this paper is that the data allows us for the first time to study leakage *within* firms. Leakage from the EU is understood here as the amount of CO_2 emissions re-located within multinational firms as a direct consequence of the introduction of climate policies within the EU. In Appendix A we introduce this more formally, but the basic idea is that multinational companies with operations across a wide range of jurisdictions might be more likely to react to regulation that imposes higher costs in some locations by shifting production to less regulated regions, because they have already incurred the cost of setting up a subsidiary in a foreign country.

The carbon leakage hypothesis is explored by looking at two types of indices of firm-level changes in emissions. First, we compare the growth rate of a firm's EU and non-EU (RoW) emissions:

$$g_{it}^{R} = \frac{CO2_{it}^{R} - CO2_{it-1}^{R}}{0.5\,(CO2_{it}^{R} + CO2_{it-1}^{R})} \tag{1}$$

where $R \in \{EU, RoW\}$. An indication for leakage would be the finding of negative emission

Figure 3: Distribution of Companies across Industries where ETS Firms Operate



growth in the EU that goes along with positive emission growth in the rest of the world. If firms subject to climate regulation also have stronger positive demand shocks or weaker productivity shocks than non or less regulated control firms, then leakage would imply that EU emissions grow slower that RoW emissions.

Secondly, we examine firm-level changes in the share of emissions from within the EU:

$$\Delta s_{it}^{EU} = s_{it}^{EU} - s_{it-1}^{EU} \tag{2}$$

where $s_{it}^{EU} = \frac{s_{it}^{EU}}{s_{it}^{EU} + s_{it}^{RoW}}$ is the share of EU CO_2 emissions for firm i at time t. If carbon was systematically leaking from the EU within MNEs, we would expect $\Delta SHEU_{it}$ to be on average negative, and even more so for firms most targeted by climate policies such as the EU ETS. An advantage of looking at the EU share is that it neutralizes the effect of non-climate policy shocks that affect all production locations of a firm uniformly.

The effects of the EU ETS are then examined by running regressions of the form:

$$\Delta s_{it}^{EU} = \beta ETS_i + \gamma X_{it} + \varepsilon_{it} \tag{3}$$

where ETS_i is an indicator variable equal to 1 for firms regulated by the EU ETS and X_{it} is a vector of control variables.

Note that unfortunately the CDP data only covers years that have followed the introduction of the EU ETS. However, we can assume that CO_2 emissions are complementary to fixed capital investments. Therefore, there is likely to be an adjustment period in response to changes in the businesses environment (such as the introduction of the EU ETS) such that the effects of a policy change could be obseved for an extended period.

The main parameter of interest is β which is expected to be strictly negative if the carbon leakage hypothesis is true. The estimation of β could be affected by any source of unobserved heterogeneity between ETS and non-ETS firms. For instance, ETS firms by definition have to be located in the EU (at some point) whereas this isn't the case for non-ETS firms. Moreover, ETS firms are exclusively 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

all the previous specifications are repeated restricting the sample to manufacturingfirms.. We further refine the analysis, running the regressions on a sub-sample of firms that belong to sectors deemed "at risk of carbon-leakage" by the EU Commission. 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 D for a list of those sectors).

4 Results

Table 1 reports the descriptive statistics for all 1785 companies in the sample.

In Table 2, we compare ETS and non-ETS companies using t-tests. Not surprisingly, ETS firms emit more both in European and non-European countries, and most of their production tends to be located in Europe. ETS firms are on average characterized by a higher turnover and a higher number of employees, while they are similar to non-ETS firms in assets.

Table 1: Descriptive Statistics

Variables	Mean	Stand. Dev.	Obs.	Source
CO2 Emissions within Europe (Million t CO2e)	0.98	8.21	1785	CDP
CO2 Emissions outside Europe (Million t CO2e)	2.46	11.12	1785	CDP
Share of CO2 Emissions within Europe	0.34	0.41	1785	CDP
Operating Revenue (Million Euro)	10047.93	20802.68	1763	ORBIS
Total Assets (Million Euro)	40371.59	159859.95	1754	ORBIS
Employees (in Thousands)	35.75	82.01	1573	ORBIS

Table 2: ETS vs non-ETS Firms

Variables	*ETS Firms* Mean (Stand. Dev.)	*Non-ETS Firms* Mean (Stand. Dev.)	Difference of Means [p-value]
All Firms (N= 1785)			
CO2 Emissions within Europe (Million t CO2e)	6.49 (1.71)	0.15 (0.07)	6.34*** [0.00]
CO2 Emissions outside Europe (Million t CO2e)	4.22 (13.18)	2.22 (11.09)	2.00** [0.03]
Share of CO2 Emissions within Europe	0.62 (0.37)	0.29 (0.40)	0.33*** [0.00]
Operating Revenue (Million Euro)	24239.77 (2706.82)	7031.95 (15063.02)	17207.82*** [0.00]
Total Assets (Million Euro)	53595.43 (153737.00)	36245.54 (152479.7)	17349.9 [0.15]
Employees (in Thousands)	66.04 (93.53)	29.11 (79.83)	36.93*** [0.00]

Notes: The p-value is taken from a two-sided t-test with equal variances. ***p<0.01, **p<0.05, *p<0.1. The number of firms N refers to the total number of firms in the sample. Not all firms report all firm level characteristics.

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.[4] Panel (a) shows the distribution for all firms with non-zero EU emissions in the base year. Panel (b) reports only ETS 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 most firms don't change their carbon emissions very much. There is also a notable mass of firms with positive growth in both EU and RoW emissions. Panel (b) suggests that emissions growth is more heterogenous in ETS firms with a more uniform distribution. 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 acti vity in these

[4]See equation 1.

sectors rather than leakage activity.

Figure 5 shows the share of CO_2 emissions in Europe over the period 2007-2014 for the full sample of ETS and non-ETS firms. It is consistent with the evidence presented in Table 2, showing that ETS firms generate a larger share of emissions in Europe compared to non-ETS firms. From 2007 to 2008, non-ETS firms display a slight increase in this measure compared to a constant share experienced by ETS companies. However, on average the two groups follow a similar trend and the gap between them remains fairly stable over the period.

Turning to the results relative to the share of EU emissions, Table 3 reports the main regressions results with the share of EU emissions as the dependent variable. Panel A reports regressions for all firms in our sample, Panel B reports on manufacturing firms and Panel C on firms in sectors considered at risk of carbon leakage according to the classification by the EU Commission (Emissions Trading Directive 2009/29/EC). As discussed above, the Commission determines if a sector is at risk by looking at carbon and trade intensity.

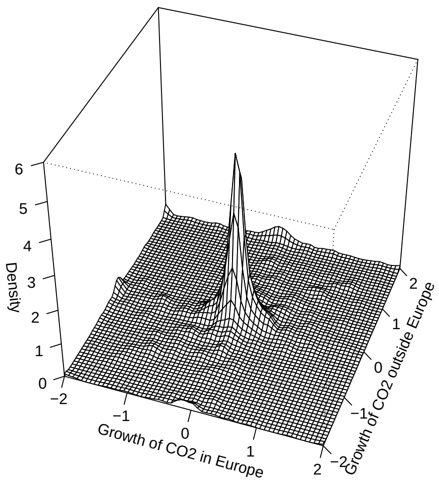
Moving through the columns of Table 3 we impose different restrictions regarding regional presence of firms. In column 2 we only include companies reporting positive emissions *both* in EU and RoW although not necessarily at the same time. Column 3 includes only observations from companies with positive EU emissions in the first period $(t-1)$. Finally, column 4 includes firms with positive EU emissions in the first period *and* non zero RoW at some point over the sample. The sub-samples created by cycling through both the panels and columns of Table 3 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.[5] 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 that leakage effects are 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 3. Furthermore, it is estimated to be very small, compared to a share of around 60% in CO2 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

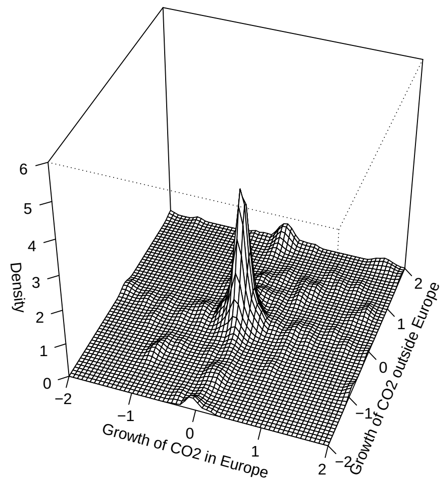
[5]A company can only be regulated by the EU ETS if it has emissions within the EU.

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) Firms ETS firms



(c) Overlaid contour plots

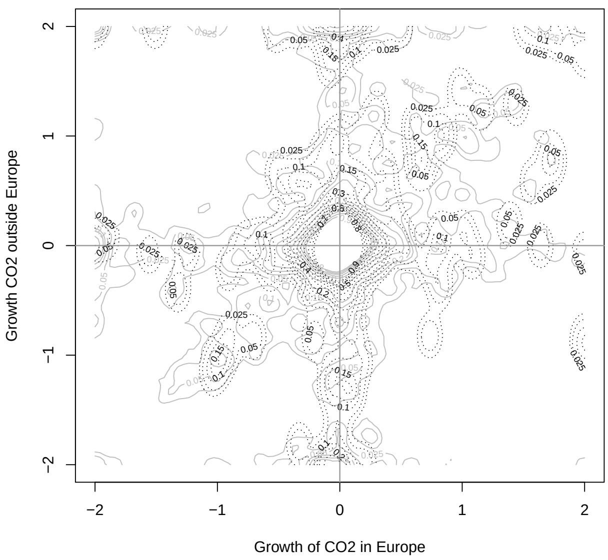
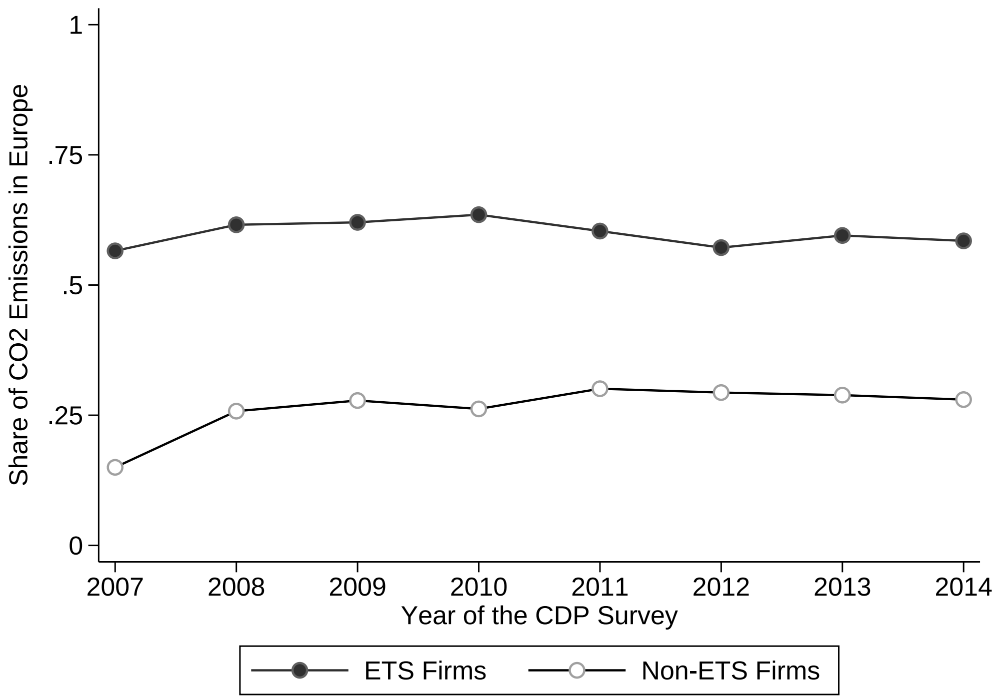


Figure 5: Share of CO_2 Emissions in Europe for ETS and non ETS Firms



different from 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 CO2 emissions in an EU ETS-regulated country in the first period and positive CO2 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 for a leakage effect, which would be characterized by a negative and statistically significant coefficient.

We have conducted a number of variations of the analysis reported in Table 3 for robustness purposes. Some of these are reported in Appendix C. For instance we repeat the estimations in Table 3 with additional control variables such as changes in capital stocks, turnover or the number of employees. We also check that our results are robust to our definition of which companies are regulated under the EU ETS (see Appendix A).

5 Conclusions

This paper uses a unique dataset that combines firm-level carbon emissions data with financial information to study the distribution of carbon emissions within multinational firms across countries and over time. We focus on the concern that EU climate policy, particularly its

Table 3: Regressions of the share of emissions in EU

	(1)	(2)	(3)	(4)
	Change in the share of EU emissions			
Panel A: All firms				
ETS Company	0.003	0.007	0.010	0.010
	(0.005)	(0.006)	(0.006)	(0.006)
Observations	3,772	2,838	2,366	2,366
R-squared	0.003	0.004	0.005	0.005
Number of firms	1134	785	674	674
Number of EU ETS firms	235	213	191	191
Panel B: Manufacturing firms				
ETS Company	0.006	0.010	0.014	0.014
	(0.006)	(0.008)	(0.009)	(0.009)
Observations	1,966	1,559	1,243	1,243
R-squared	0.003	0.004	0.007	0.007
Number of firms	565	421	348	348
Number of EU ETS firms	153	145	127	127
Panel C: Manufacturing firms at risk of carbon leakage				
ETS Company	0.004	0.008	0.013	0.013
	(0.006)	(0.007)	(0.009)	(0.009)
Observations	1,542	1,212	967	967
R-squared	0.006	0.008	0.013	0.013
Number of firms	446	336	277	277
Number of EU ETS firms	115	112	98	98

Notes: ETS Company equals 1 if a company owns an installation that is regulated under the EU ETS and 0 otherwise. Columns (1): all companies, (2): companies reporting positive missions both within and outside the EU ETS countries at some point in time, (3): companies reporting positive emissions within the EU ETS countries in the first period, (4): companies reporting positive emissions within the EU ETS countries in the first period and positive emissions outside the EU ETS countries at some point in time. Firms at risk of carbon leakage are defined as in Martin et al. (2014). Manufacturing firms are coded as "C-Manufacturing" in the NACE Rev.2 Main Section classification. Standard errors are clustered at the company level, shown in parentheses. ***p<0.01, **p<0.05, *p<0.01. Model includes a constant.

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 do not 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? This is an immediate question arising from the evidence we provide based on multinational companies that should 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 for free to carbon-intensive and trade-exposed industries, is successfully prevent leakage effects.[6] 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 on the European market has fluctuated between 0 and 30 euros per tonne over the last 10 years, being most time in the lower range of this interval. Yet it is likely that the threats posed by climate change will require regulations that lie far outside the bounds of past experience. At the same time the regulatory gap could also narrow in the future with emerging economies such as China,implementing more stringent climate policy than in the past.

[6]Indeed Yet, Martin et al. (2014) aruge that the EU Commission is handing out free permits more generously than necessary.

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A A simple model of carbon leakage

This sections introduces a simple model to make precise our definition of Carbon Leakage. We consider firms producing 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 form:

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

where A_{EU} and A_{RoW} are region specific productivity shocks. Suppose that carbon emissions are a linear function of capital: $CO2_R = \rho K_R$ for $R \in \{EU, RoW\}$. For simplicity suppose that capital (user) 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:

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

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

Emissions in each location are then given by:

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

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

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:

$$CO2_{EU} = \Lambda^{\eta-1}\mu^{-\eta}c\left(r, \tau\right)^{\gamma-\eta} A_{EU}^{\gamma-1}\left(r + \rho\tau\right)^{-\gamma} \tag{4}$$

$$CO2_{RoW} = \Lambda^{\eta-1}\mu^{-\eta}c\left(r, \tau\right)^{\gamma-\eta} A_{EU}^{\gamma-1} r^{-\gamma} \tag{5}$$

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

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

Looking at equation 5 we see that leakage will occur if the cost increase from a change in τ has a negative effect on CO_2 emissions in RoW, which will be the case if $\gamma > \eta$. Put differently, leakage will not occur if EU and RoW capital are highly complementary ($\gamma \to 0$) or if the demand for a firm's output is highly elastic ($\eta \to \infty$). Equation 5 also illustrates what it takes detect and quantify leakage in our firm level data: we would need controls for region specific shocks as well as firm specific shocks apart from changes in carbon prices or appropriate instruments. Alternatively, consider the equations 4 and 5 in terms of differences of log changes, i.e. approximately the difference in growth rates:

$$\Delta \ln CO2_{EU} - \Delta \ln CO2_{RoW} = (\gamma - 1) \Delta \ln A_{EU} - \gamma \Delta \ln (r + \rho\tau) - (\gamma - 1) \Delta \ln A_{RoW} + \gamma \Delta \ln r \tag{6}$$

Suppose a firm experience and increase in carbon prices from 0 to τ due to the ETS. We can re-write 6 approximately as

$$\Delta \ln CO2_{EU} - \Delta \ln CO2_{RoW} \approx (\gamma - 1) \Delta \ln A_{EU} - (\gamma - 1) \Delta \ln A_{RoW} - \frac{\gamma}{r} \rho\tau$$

In other words if EU and RoW capital services are highly substitutable (γ is large), the carbon price increase τ is large relative to other capital cost factors r and other region specific productivity shocks have only confounding influence, then we should see that EU CO_2 emissions grow more slowly than RoW emissions.

Similarly, we can look at the EU share in emissions:

$$s_{EU} = \frac{A_{EU}^{\gamma-1} (r + \rho\tau)^{-\gamma}}{A_{ROW}^{\gamma-1} r^{-\gamma}}$$

Hence, provided that region specific productivity shocks are not confounding things, an increase in carbon prices τ should lead to a reduced EU share if there leakage is occurring.

B Coding companies as treated by the EU ETS

This section discusses how companies in the CDP were assigned a treatment status by the EU ETS. The data on multinational companies comes from the CDP survey that is aimed at large companies operating in several countries and that are often listed. Data on the installations that are regulated under the EU ETS, by contrast, comes from the European Union Transaction Log (EUTL). The challenge, therefore, lies in matching EU ETS *installations* to *multinational companies*. The most consistent way to perform this match is to use the Bureau van Dijk company identifier, which we construct from the CDP data using the ORBIS database.

Using the ORBIS database, the Bureau van Dijk identifier can then be used to match the CDP multinationals to the EUTL installations that they own. Figure 6 shows that there exist different possible ownership levels: the owning company (or immediate shareholder), the domestic ultimate owner and the global ultimate owner. Given that our aim is to match multinational companies to EUTL installations, either the domestic ultimate owner or the global ultimate owner needs to be used. Our preferred treatment coding is based on the domestic ultimate owner, because using the global ultimate owner might introduce an attenuation bias that would go against the possibility of finding a leakage effect.

Figure 6: Different EU ETS installation ownership levels

Figure 7 shows how the number of treated firms in our sample changes depending on the coding of the EU ETS company treatment dummy. As can be seen, using the global ultimate owner unsurprisingly yields more matches to the EUTL installations than the our preferred domestic ultimate owner. To avoid biasing our control group, we exclude firms that would have been coded as EU ETS firms by any of the other codings but not the coding at hand. That is a firm that is the global ultimate owner of an EUTL installation but not also its domestic ultimate owner will be dropped for the estimations. This is the case for 93 companies. Additionally, in the future, we will make use of information in some vintages of the CDP survey as to which companies are regulated by the EU ETS.

Figure 7: Number of EU ETS firms depending on coding

Level of Coding	# EU ETS Firms
EUTL Installation	78
Domestic Ultimate Owner	**142**
Immediate Shareholder	185
Global Ultimate Owner	235

Most important, however, is the robustness of our results to the choice of coding: while an important concern in theory, the coding of the EU ETS firms does not affect the results in practice. There is no leakage effect for any of the codings that are possible. These results are available upon request.

C Additional specifications with added control variables

Table 4: Regressions of the share of emissions in EU

	(1)	(2)	(3)	(4)
	Change in the share of EU emissions			
Panel A: All firms				
ETS Company	0.002	0.006	0.008	0.008
	(0.005)	(0.006)	(0.007)	(0.007)
Controls	YES	YES	YES	YES
Observations	3,351	2,635	2,205	2,205
R-squared	0.003	0.004	0.005	0.005
Number of firms	995	723	622	622
Number of EU ETS firms	218	202	180	180
Panel B: Manufacturing firms				
ETS Company	0.005	0.008	0.011	0.011
	(0.007)	(0.008)	(0.009)	(0.009)
Controls	YES	YES	YES	YES
Observations	1,813	1,492	1,200	1,200
R-squared	0.005	0.006	0.008	0.008
Number of firms	518	402	334	334
Number of EU ETS firms	150	144	126	126
Panel C: Manufacturing firms at risk of carbon leakage				
ETS Company	0.005	0.009	0.012	0.012
	(0.007)	(0.008)	(0.009)	(0.009)
Controls	YES	YES	YES	YES
Observations	1,413	1,164	935	935
R-squared	0.007	0.009	0.015	0.015
Number of firms	404	319	265	265
Number of EU ETS firms	112	111	97	97

Notes: ETS Company equals 1 if a company owns an installation that is regulated under the EU ETS and 0 otherwise. Conrols are revenue, number of employees, and assets at the company level. Columns (1): all companies, (2): companies reporting positive missions both within and outside the EU ETS countries at some point in time, (3): companies reporting positive emissions within the EU ETS countries in the first period, (4): companies reporting positive emissions within the EU ETS countries in the first period and positive emissions outside the EU ETS countries at some point in time. Standard errors are clustered at the company level, shown in parentheses. ***p<0.01, **p<0.05, *p<0.01. Model includes a constant.

D List of sectors judged at risk of carbon leakage

The following table lists all sectors that are coded at risk of carbon leakage (as detailled 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 generalpurpose 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 specialpurpose 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