October 2022

Fondazione Eni Enrico Mattei

Working Paper

027.2022

Environmental Policy and Investment Location: The Risk of Carbon Leakage in the EU ETS

Filippo Maria D'Arcangelo, Marzio Galeotti

Environmental Policy and Investment Location: The Risk of Carbon Leakage in the EU ETS

By Filippo Maria **D'Arcangelo** (OECD, Economics Department) Marzio **Galeotti** (Department of Environmental Science and Policy, University of Milan and Fondazione Eni Enrico Mattei)

Summary

This paper empirically investigates the effect of the European Emission Trading Scheme (EU ETS) on cross-country investments. To avoid carbon leakage, the scheme allocates a number of free allowances to firms at risk of relocating investments in areas outside the EU ETS. To study this problem, we employ a model of the firm's investment decision in conjunction with novel firm-level data. In contrast with most previous literature, we stress the importance of firms' heterogeneity in the analysis and leverage it. We derive conditions for the firm's optimal emissions to construct a measure of investment sensitivity to carbon pricing from observed pollution data. This allows to identify the effect of the EU ETS on international investments by comparing the expected profits from investing in several different countries. We find that investments react to carbon pricing and that the effect is stronger for more polluting investments. However, the aggregate amount of diverted investments is small. We moreover show that the lost investments do not justify, alone,the generous compensations scheme aimed at retaining investments.

Keywords: Emission trading, carbon leakage, investment location, EU ETS
JEL Classification: D22, F18, Q52, Q54

Address for correspondence:
Marzio Galeotti
Professor, Department of Environmental Science and Policy, University of Milan
Via Celoria 2, 20133, Milan (Italy)
E-mail address: marzio.galeotti@unimi.it

Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

Environmental Policy and Investment Location: The Risk of Carbon Leakage in the EU ETS

Filippo Maria D'Arcangelo[1] Marzio Galeotti[2,3,*]

ABSTRACT

This paper empirically investigates the effect of the European Emission Trading Scheme (EU ETS) on cross-country investments. To avoid carbon leakage, the scheme allocates a number of free allowances to firms at risk of relocating investments in areas outside the EU ETS. To study this problem, we employ a model of the firm's investment decision in conjunction with novel firm-level data. In contrast with most previous literature, we stress the importance of firms' heterogeneity in the analysis and leverage it. We derive conditions for the firm's optimal emissions to construct a measure of investment sensitivity to carbon pricing from observed pollution data. This allows to identify the effect of the EU ETS on international investments by comparing the expected profits from investing in several different countries. We find that investments react to carbon pricing and that the effect is stronger for more polluting investments. However, the aggregate amount of diverted investments is small. We moreover show that the lost investments do not justify, alone, the generous compensations scheme aimed at retaining investments.

JEL codes: D22, F18, Q52, Q54

Keywords: Emission trading; carbon leakage; investment location; EU ETS

We thank for useful comments Mathias Reynaert, François Salanie, Estelle Cantillon, Olivier De Groote, Isis Durrmeyer, Natalia Fabra, Sebastian Fleitas, James K. Hammitt, Stefan Lamp, Matti Liski, Céline Nauges, Giulia Pavan, Mar Reguant, Johannes Van Biesebroeck, Frank Verboven and participants at TSE (2018, 2019), KU Leuven (2018) and OECD (2020) workshops, the EEA Virtual Congress (2020), the Twelfth Toulouse Conference on The Economics of Energy and Climate (2019), the 46th EARIE in Barcelona (2019), the Applied Economics Workshop in Petralia (2019) and at the XXXIV Jornadas de Economìa Industrial in Madrid (2019). The views expressed and arguments employed herein are those of the authors and do not necessarily reflect the official views of the OECD or the governments of its members countries.

[1] OECD, Economics Department, Paris, France
[2] Department of Environmental Science and Policy, University of Milan
[3] Fondazione Eni Enrico Mattei, Milan, Italy
* Corresponding author: Marzio Galeotti, Department of Environmental Science and Policy, University of Milan, Via Celoria 2, I-20133 Milan, Italy. marzio.galeotti@unimi.it

Environmental Policy and Investment Location: The Risk of Carbon Leakage in the EU ETS

1. Introduction

The Emission Trading Scheme (EU ETS) is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. Capping the emissions of carbon dioxide, nitrous oxide and perfluorocarbons from over 11 000 heavy energy-using and electricity generating installations and aircraft, covering about 45% of the EU's greenhouse gas (GHG) emissions, it is the world's first major carbon market and remains the biggest one.

At the beginning of 2021 in the midst of the pandemic crisis, the EU ETS has entered its fourth trading period (Phase IV, from 2021 to 2030) under a newly revised legislation. The rules governing the allocation of emission allowances are a fundamental component of the system's regulation, which has changed significantly across the trading periods as part of wider reforms.

Asymmetric climate action across jurisdictions raises a problem of protecting domestic producers from competitiveness loss due to higher production-cum-carbon costs and avoiding the risk of relocation of production activities in places with laxer climate policy. The risk of this phenomenon, referred to as carbon leakage, may be higher in certain energy-intensive industries, such as steel and aluminum. Under the EU ETS, to limit the displacement of emissions compensation is offered taking the form of free tradable permits to pollute (allowances) assigned to specific industries.

Since the launch of the ETS in 2005, EU industries have followed divergent greenhouse gas trajectories: while the power sector has cut them by half, cement and steelmakers, which got free allowances for four-fifths of their exhausts, have barely decreased their emissions. To stop this, under the European Green Deal the European Commission in July 2021 has proposed replacing free allowances by a new Carbon Border Adjustment Mechanism (CBAM) under which importers would have to buy carbon certificates corresponding to the price paid by European manufacturers. Foreign producers would be exempted from the levy only if they can show that they paid a similar carbon price at home. And importers would then pay the difference. Under the Commission's proposal, CBAM will be phased in as of 2026 for a period of ten years, by which time EU industries covered by the scheme will stop receiving free CO2 permits on the EU carbon market. The policy of free allowances will continue in Phase 4 (2021-2030) of the EU ETS but based on more stringent criteria and improved data.

One question that remains relatively unaddressed is the extent of the risk of relocation against which free allowances are issued. To determine the appropriate magnitude of these compensations, it is essential to estimate how the firms' propensity to locate their investments changes because of carbon pricing and the emissions associated with these investments. The empirical evidence on this issue is scant. Indeed, only a handful of papers shed some light on carbon leakage within the EU ETS framework (Martin et al., 2014a; Martin et al, 2014b; Borghesi et al., 2020; Koch and Basse Mama, 2019; Dechezleprêtre et al., 2022).

This paper estimates the effect of the EU ETS on carbon leakage focusing on cross-country investments. Using detailed firm-level data, a model of the firms' production and investment decisions is presented that allows to estimate how the probability of locating the productive capacity in a country responds to the price of carbon in that country. The analytical framework provides an estimable link between the data and carbon leakage. Firms that employ a more energy intensive technology, or that cannot easily switch to less polluting fuels, emit more and thus need to buy more pollution rights. Therefore, such firms are more likely to locate their investments outside of the EU ETS, everything else equal. By choosing a location outside of Europe, the firm trades off a lower price of carbon for higher installation and operating costs. To capture this mechanism, we model the firm's production choices linking emission intensity to energy and carbon prices and to its technology. In so doing we can identify each firm's output elasticity to energy use, which drives the sensitivity of the firm to the policy and affects the probability of investing within the EU ETS. This approach innovates over the use of realized emission intensity to construct a measure of policy severity. Realized emission intensities depend on energy and carbon prices and are thus endogenous to the policy.

The second main contribution is the development of a novel dataset that combines emissions and investment data for a panel of European individual firms. While between-industry heterogeneity has been emphasized in the literature (Keller and Levinson, 2002; Brunnermeier and Levinson, 2004; Millimet and Roy, 2016; Dechezleprêtre and Sato, 2017), little attention has been devoted to heterogeneity between firms, mostly for lack of firm-level data (Fowlie and Reguant, 2018). Absent this type of data, most of the empirical analysis has turned to comparisons between industries. However, firms are substantially different in energy use and emissions, even when they produce very similar goods (Lyubich et al., 2018). More polluting firms are more affected by an environmental policy and may thus react more strongly. Ignoring this source of heterogeneity is problematic for three reasons. First, the use of industry aggregates instead of firm-level measures introduces an aggregation error. This error causes an attenuation bias, resulting in an erroneous estimation of the firms' response to the environmental regulation. Second, the most polluting firms have the highest incentive to locate their production abroad and could be the first to do so (Copeland, 2008). If all firms within an industry are instead assumed to pollute the same amount, this selection problem leads to underestimate the displaced emissions. Third, the decision to offer compensation for carbon leakage is often taken on an industry-by-industry criterion rather than on an individual firm basis. This fact disregards that, within an industry, firms have different propensities to relocate and are more or less polluting, i.e. they contribute differently to the risk of carbon leakage and should ideally be compensated accordingly.

The EU ETS provides an especially well-suited environment to study carbon leakage using firm-level data because the information on emissions produced is available for each emitting source. We focus the analysis on manufacturing and energy producing firms covered by the EU ETS and their cross-country investments in new productive capacity, i.e. green-field investments, over the period 2005 to 2012. The analysis of greenfield investments is particularly appropriate for capturing the extensive margin effect of the EU ETS on carbon leakage. These investments are motivated solely by the installation of new productive capacity, thus we can rule out other reasons for investment, such as purely financial investments or brand and technology acquisition. Moreover, since the compensations for carbon leakage have the stated objective of keeping productive capacity within the EU ETS, greenfield investments are the natural candidate for this analysis.

The empirical estimation is comprised of two stages. We recover the firm's expected compliance costs in each location in the first stage. These costs are not directly observable but can be inferred from the data, invoking the conditions derived in the theoretical model. Here we find strong support for within-industry heterogeneity, with output elasticities to energy being as much as 37 times larger in the 75th percentile (0.32) than in the 25th percentile

(0.008). Emission intensities are elastic to the allowance prices (-1.5) but fairly inelastic to the price of energy (-0.1). Nevertheless, the same volume of investment can be expected to generate as much as 15 times more emissions in a country with no carbon pricing and low coal and oil prices. The second stage relates the choice of investing to the expected costs of emitting in a country. A discrete choice model is estimated where the firm chooses whether and where to invest among a rich set of countries based on the difference in expected profits. We find that investments respond negatively to carbon pricing, but this effect is small in magnitude. These small and precisely estimated effects are robust to different specifications. Importantly, this effect is shown to disappear when firm heterogeneity is not taken into account, thus underlining the importance of firm-level analysis. The model predictions are analyzed under two policy-relevant scenarios. First, we predict how the probabilities of investing in each country change with an increase in the allowance price to 30 euros over the period 2005-2012. Second, we consider the case in which no free allowance is allocated to firms.

Overall, this study finds that carbon pricing has discouraged investments in Europe in the context of the EU ETS. However, it also finds that the aggregate magnitude of diverted investments is economically small, suggesting that this motive alone does not justify the generous compensation scheme that has been in place until today.

The structure of the paper is as follows: Section 2 describes the institutional details of the EU ETS and how the compensation scheme works; Section 3 presents the theoretical model; Section 4 presents the data; Section 5 discusses the empirical strategy and presents the main results; Section 6 presents the implications for policy, while Section 7 discuss the robustness checks before concluding.

2. Background

2.1 Related literature

This paper contributes to a large literature on pollution havens and carbon leakage. The pollution haven hypothesis (PHH) posits that the compliance costs associated with an environmental policy impair the competitiveness of polluting firms, which thus flee towards countries with a laxer regulation (Copeland and Taylor, 2005). Within the PHH literature, the papers that most relate to the present study are those using investment and plant location data.[1] This literature argues that the introduction of an environmental policy affects negatively the productivity of capital. Therefore, capital reallocates to equalize its global rate of return causing an outflow of foreign direct investments.[2]

This paper contributes to the PHH literature by introducing firm-level heterogeneity. Most other studies rely on aggregated measures of abatement costs, such as survey indicators (Wagner and Timmins, 2009), industry expenditures for environmental protection (List and Co, 2000; Keller and Levinson, 2002; Brunnermeier and Levinson, 2004), average industry energy or emission intensity (Xing and Kolstad, 2002; List et al., 2003, 2004) and industry indicators for energy prices (Aldy and Pizer, 2015; Fowlie et al., 2016; Fowlie and Reguant, 2018; Saussay and Sato, 2018).[3] These measures are usually considered at industry level, even when firm-level investments were available. In contrast, we use here firm-level data for both abatement costs and investments. The empirical strategy followed here, based on recovering the output elasticity to energy and building counterfactual compliance costs, can be applied in more general contexts to investigate the effect of carbon pricing on firms' outcomes.

This paper also contributes to the large literature on the effects of carbon pricing on environmental and economic outcomes, where the EU ETS represents a major policy example (Verde, 2020). Most empirical papers dealing with the evaluation of the EU ETS on firms' outcomes (European Commission, 2015; Martin et al., 2016) suggest a cohesive theme: firms responded to carbon pricing by reducing emissions (Petrick and Wagner, 2014; Wagner et al., 2014, Colmer et al., 2020), switching fuels (Ellerman and McGuinness, 2008) and innovating (Calel and Dechezleprêtre, 2016). But they did not reduce employment (Commins et al., 2011) and profits (Martin et al., 2016) or lose productivity (Jaraité and Di Maria, 2012; D'Arcangelo

[1] Alternatively, and more frequently, pollution haven studies have considered trade flows: see Jaffe et al. (1995), Copeland and Taylor (2004), and Brunnermeier and Levinson (2004) for reviews on the use of trade data in investigating the pollution haven hypothesis. More recently, Aichele and Felbermayr (2015) address specifically the carbon leakage problem, performing an ex-post analysis of the Kyoto protocol.

[2] See Jeppesen et al. (2002) for a review of early contributions.

[3] These last papers investigate how an increase in energy cost can be used to infer the increase in costs due to carbon pricing, and thus carbon leakage. They are therefore closely related to the present paper. Fowlie et al. (2016) and Fowlie and Reguant (2018) estimate the elasticity of production, imports and exports to energy prices, capturing between-industry heterogeneity, and use the estimates to simulate the effect of $10/tCO2 carbon price on these variables. Saussay and Sato (2018) use rich data on mergers and acquisition of multinational firms to study how they are affected by differences in a country energy price index. This paper directly uses emissions data and builds on their intuition that energy prices are an important element in assessing firms' response to carbon pricing. As shown below, we do so by explicitly allowing emissions to depend on energy prices.

et al., 2022). Indeed, certain industries, like power generators, benefited from the EU ETS cashing on the free allowances (Veith et al., 2009; Bushnell et al., 2013) and passing-through the price of carbon to consumers (Verde et al., 2019; Cludius et al., 2020). In line with these results, the findings on international investments in this paper add evidence and support to the argument that the EU ETS has not jeopardized Europe's competitiveness.

Finally, this paper contributes to the empirical evidence on the effect of the EU ETS on investment leakage.[4] Martin et al. (2014a; 2014b) use interviews to the managers of more than 700 firms of six countries to assess the risk of carbon leakage for manufacturing firms. The authors find that economic activity is not likely to contract because of carbon pricing, although more emission intensive firms could display a stronger response. Borghesi et al. (2020) investigate whether the EU ETS had any effect on outward FDIs of regulated manufacturing firms in Italy. They use a difference-in-difference approach applied to sample extracted from the Aida database of Italian companies from 2002 to 2010. The sub-samples for years 2002-2004, 2005-2007, and 2008-2010 used for estimations include treatment groups of 283 regulated firms. The authors find a positive weak effect on the number of new subsidiaries abroad and a larger effect on the production occurring in foreign subsidiaries, especially in trade-intensive sectors. Considering outward FDI of German multinationals, Koch and Basse Mama (2016) obtain similar results , again using a difference-in-differences with bias-corrected matching estimator. The authors find that only a small subset of firms significantly increased their FDI out of Europe, compared with a counterfactual scenario. However, such firms do not belong to the sectors at risk of relocation according to the EU criteria, but rather to sectors that are less capital intensive, and therefore more geographically mobile. Using a sample from database of the Carbon Disclosure Project covering 1122 companies (261 regulated) over the period 2007–2014, Dechezleprêtre et al. (2022) study whether emissions from subsidiaries belonging to the same multinational firm react differently if the subsidiary is located outside or inside the EU ETS. They find no evidence of any carbon leakage effect in general, and the same applies with respect to those sectors deemed at risk of carbon leakage.

[4] Earlier works used computable general equilibrium models to provide ex-ante assessments of regional policies on carbon leakage. While these models can capture every channel of carbon leakage, they often rely on very restrictive assumptions on markets, technology and trade. Carbone and Rivers (2017) review this work.

Rather than through survey evidence as in Martin et al. (2014a; 2014b), in this paper we provide direct estimates on the magnitude of these effects using observational data. While in papers such as Koch and Basse Mama (2016) and Borghesi et al. (2020) identification relies on a difference-in-differences approach, augmented with methods to correct selection, the definition of a control group proves typically difficult (see also Verde, 2020). In contrast, we propose here a different methodology which leverages idiosyncratic differences between treated firms to identify the causal effect of the EU ETS on firms and that can be easily applied to other contexts in which emission data are available. Finally, the results of the above papers including Dechezleprêtre et al. (2022) complement those contained here as they can't be used to evaluate changes in the policy, e.g. in the compensation scheme, because they do not provide a model of the firm's behavior, as done in this paper.

2.2 EU ETS and free allowances allocation and compensation rules

The rules governing the allocation of emission allowances are a fundamental component of the EU ETS setup. In a cap-and-trade system such as the EU ETS, allowances can be distributed to installations for free, through auctions, or using a mix of the two methods. The mixed method represents the most common case for systems that are not limited to the power sector, where auctioning is the standard option, while for other sectors a portion of free allowances is always distributed to regulated firms.

In the EU ETS free allocation rules have significantly changed over trading periods as part of wider reforms, including the latest changes for Phase IV.[5] During both Phase I (2005-2007) and Phase II (2008-2012) "grandfathering" was the basic allocation regime. Determining the total volume of allowances and their allocation was the responsibility of national governments through the so-called National Allocation Plans (NAPs). They could auction up to 5% and 10% of the total number of allowances in Phase I and Phase II, respectively, based on emissions at plant level. In practice during Phase 1 the entirety of the EUAs available in the EU ETS was allocated to firms for free, while the proportion of free allowances declined in Phase 2 to around 94%.

[5] See Ellerman et al. (2016) and https://fsr.eui.eu/eu-emission-trading-system-eu-ets/ for details on the reform process.

In Phase 3 (2013-2020) the major institutional innovation was the centralization of the system: the total volume of allowances was now determined in Brussels. The allocation regime was radically changed: auctioning became the default allocation method for electricity generating installations, while for all other installations benchmarked allocation was introduced. The application of emission efficiency benchmarks is combined with the identification of the sectors at risk of carbon leakage. Installations in the sectors deemed at significant risk of carbon leakage are given free allowances covering 100% of their benchmarked emissions, whereas for the other sectors free allowances cover progressively smaller shares of benchmarked emissions, from 80% in 2013 to as little as 30% in 2020.

The reform for Phase IV (2013-2020) includes better-targeting free allocation. The new rule is more stringent than the one applied in Phase III, so that the number of sectors classified as being at risk will shrink.

The case of free allocation represents an aspect of special interest for the implications in terms of both equity and competitiveness (Flues and van Dender, 2017; Verde et al., 2020). Absent frictions, the initial allowances allocation should not affect the efficiency of the policy, in application of Coase theorem. Notwithstanding, recipients do benefit from free allowances, regardless of whether they use them to offset their own emissions or to resell them. Therefore, the free allocation of allowances is potentially problematic, as the associated rent violates the "polluter pays-principle", as stated in the Treaty on the Functioning of the European Union (Article 191(2)).

As to competitiveness concerns and the risk of carbon leakage, the allocation of free allowances was in practice based on historical emissions until 2011 ("grandfathering"). Since 2012, the allocation is based on product benchmarks, defined for 52 product classes (e.g. iron casting, uncoated carton board, white cement clinker). It is defined as the average emission intensity of the 10 percent best performing regulated installations producing that product in terms of CO_2 per ton of product.[6] Since Phase 3, new investments are entitled to free allowances, calculated on the capacity installed and applying the same product benchmarks.

[6] The only factor in the allocation that varies by firm is the "historical activity level". This activity level is based on the years 2005-2008 (and/or 2009-2010 if available) and calculated on the production volumes. The installed output or thermal capacity are instead used if historical volumes are missing.

It is therefore important to take into account this aspect when calculating the total effect of the EU ETS on investments.

An important exemption from auctioning is provided to sectors deemed at a significant risk of carbon leakage. Firms in these manufacturing sectors (but not electricity producers) continue to receive allowances for free: after applying the industry benchmark, free allowances in exempted industries are expected to entirely cover demand in these industries. These sectors are defined at a 4-digit or 6-digit product classification code on the basis of two sector-wide criteria: trade intensity and carbon intensity. Trade intensity is calculated as the ratio between the total value of exports to third countries plus the value of imports from third countries and the total market size for the Union. Carbon intensity is proxied by summing sectoral estimates of direct and indirect costs of carbon pricing divided by the gross value added of the sector.[7] The industries at risk of carbon leakage are categorized in one of three ways: A) carbon intensity above 0.3; B) trade intensity above 0.3; or C) carbon intensity above 0.05 and trade intensity above 0.1.[8] The exemption coverage is quite considerable, as it applies to approximately half of the firms in the EU ETS (Martin et al., 2014a). Firms exempted from auctioning received between 600 and 800 million free allowances per year. While auctioning was progressively introduced in other industries, it did not apply to exempted industries. In 2017, the difference generated as much as 1.1 bn€ in additional profits for the exempted firms, i.e. around €390 000 on average per firm.[9]

Because of data limitations, the empirical application in this paper focuses on the first two phases, in which auctioning was in practice not used. The advantage is that all firms were under the same regime, eliminating a possible confounding channel in explaining firms' behavior, which we now model.

---

[7] Direct costs are calculated on a price proxy of e30 per ton of CO2 produced, even though the price of allowances has historically been much lower. Indirect costs proxy the higher costs of electricity, calculated on the basis of national consumption data and considering the same proxy price.

[8] In Phase IV, as a rule, a sector will be classified as being at risk of carbon leakage if the product of the carbon emissions intensity indicator (CeI) (expressed in terms of KgCO2 per Euro of gross value added) and the TI indicator, $CeI \times TI$, exceeds 0.2. This rule is more stringent than the one applied in Phase III.

[9] Details on these calculations are given in Appendix A.

3. The model

To motivate the empirical analysis that follows we introduce a model designed to capture the effect of carbon pricing on the firm's investment location decisions. The main elements that determine whether a polluting investment will be located under the EU ETS are the allowance price, the free allowances received, and how energy intensive is the technology employed by the firm. This last factor is key: even in the same industry, firms employ energy to very different extents and energy use is related to emissions. Because firms are heterogeneous in emission intensity, firms with higher emissions are more sensitive to the policy. The model provides a framework that allows to recover compliance costs from observed emissions and to calculate these costs for new investments.

The model description proceeds in two steps. Firstly, we look at the firm's choice of energy sources. The data does not contain firm-level energy use nor demand for energy sources, but energy prices are observed for several locations. It is therefore useful to rewrite the problem in terms of emissions, rather than in terms of energy choices. We therefore derive the firm's choice for emissions, which crucially depend on the output elasticity to energy. This condition is used to infer the firm's expected compliance costs with the policy in each location, which are not observed. Secondly, we model how the decision of investing internationally is influenced by these costs.

3.1 The firm's emissions choice

A price-taking firm uses energy and other inputs to produce an output Y according to a production function that is assumed to be homogeneous in energy use. That is:

$$Y = E^{\alpha}F(X) = \left[\left(\sum_{s=1}^{S}\eta_s e_s^{\theta}\right)^{\frac{1}{\theta}}\right]^{\alpha} F(X) \tag{1}$$

where e_s are the quantities of S energy sources (different fuels, electricity) and X is the vector of $\{x_r\}_{r=1}^{R}$ non-energy input quantities including labor, fixed capital, intermediate materials. Individual energy sources can be aggregated into a total energy input E via a CES aggregator function with substitution parameter θ and share parameters η_s reflecting the intensity of each source in the production of energy.[10] We make this assumption for illustrative purposes

[10] Constant returns to scale for the energy technology are assumed without loss of generality. The substitution elasticity between individual energy sources is given by $1/(1-\theta)$.

and relax it later in the empirical model. In addition, α is the output elasticity to energy use, representing the relevance of energy in production.

Using energy generates harmful emissions according to their carbon content, c_s. Since no end-of-pipe abatement technology, such as CO_2 filters or carbon sequestration, is practically in use, the carbon content of each energy source is exogenous to the firm. Total carbon emissions CE are given by the sum of emissions produced from the different energy sources, according to their carbon content:

(2) $$CE = \sum_{s=1}^{S} c_s e_s.$$

Using inputs in production is costly and energy sources e_s are purchased at unitary prices p_s^e, while other inputs are purchased at prices $p^x = \{p_r\}_{r=1}^{R}$.[11] The firm chooses the levels of inputs to maximize its profits π. The firm offsets the emissions produced by purchasing allowances at price τ but receives an endowment of free allowances CE^*. The (static) profit maximizing problem is the following:

(3) $$\max_{e_1,\dots,e_S,x_1,\dots,x_R} \pi = p^y Y - \sum_{r=1}^{R} p_r^x x_r - \sum_{s=1}^{S} p_s^e e_s - \tau(CE - CE^*)$$

subject to (1)-(2). We do not solve for the optimal input choices problem (3) because in the empirical analysis we crucially use firm-level data that does not contain information on energy use. We can get around this problem by expressing profits in terms of emissions rather than energy sources. Letting the price $\tilde{p}_s = \frac{p_s^e + \tau c_s}{\eta_s}$ we solve the following unconstrained profit maximization problem:[12]

(4) $$\max_{x_1,\dots,x_R,CE} p^y (\Omega \cdot CE)^\alpha F(X) - \sum_{r=1}^{R} p_r^x x_r - P(p^e, \tau; \eta, \theta) CE + \tau CE^*$$

where:

(5) $$\Omega = \left(\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}\right)^{-\frac{1}{\theta}} \left(\sum_{s=1}^{S} c_s \tilde{p}_s^{\frac{1}{\theta-1}}\right)$$

and $P(p_s^e, \tau; \eta, \theta)$ is the per-emission cost sustained by the firm to produce one additional unit

[11] We think of energy as being expressed in kilowatt-hours or megajoules. This notion of energy as a homogeneous good approximates well most uses in manufacturing and energy producers. For example, heat, electricity and kinetic energy are all measured in energy units.

[12] Appendix B.1 reports the details of the derivations.

of energy:

$$(6) \qquad P(p^e,\tau;\eta,\theta)=\left[\left(\sum_{s=1}^{S}\eta_s\tilde{p}_s^{\frac{\theta}{\theta-1}}\right)\left(\sum_{s=1}^{S}c_s\tilde{p}_s^{\frac{1}{\theta-1}}\right)^{-1}\right].$$

The unit cost of energy depends on the price vector of energy sources p^e, the carbon price τ, and the vector η collecting the parameters η_s and θ. Expression (3) shows how the EU ETS affects the firms' profitability through CE^* and τ. Free allowances act as a lump-sum transfer and shift profits upward by τCE^* as the firm can always sell them at market price. This free allocation of allowances does not affect the production choices because the amount is fixed for the firm. On the other hand, a higher price of carbon gives the firm an incentive to reduce CE by adjusting production, switching to less emitting fuels and readjusting other inputs. Compared to the laissez-faire case, in which the price of carbon is zero, the average cost of production increases and the difference is the compliance cost for the firm. The magnitude of this compliance cost depends on the energy mix and on the importance of energy in the production of the output.

The first order condition of problem (4) with respect to emissions states that the revenue share of an input expenditure is constant and equal to its output elasticity α. The condition can be written in terms of emissions per unit of revenue, i.e. in terms of emission intensity, e:

$$(7) \qquad e=\frac{CE}{p^yY}=\alpha\cdot P(p^e,\tau;\eta,\theta)^{-1}$$

The equilibrium emission intensity depends on two elements: (i) the output elasticity to energy α and (ii) the price of emissions $P(.)$. The output elasticity to energy captures the importance of energy in the productive process. For example, it reflects the melting or reaction temperatures of intermediate inputs, the kinetic energy needed for transformation of state or the electricity needed for machinery to work. Productive processes where energy is a key factor, such as iron or paper production, can be expected to have a higher α, everything else equal. While α evidently varies across industries, it is also likely to differ across firms within the same industry as different productive processes are often available to produce the same product. The term $P(p^e,\tau;\eta,\theta)$ is the firm's total price of emissions and depends on how the firm can organize its energy mix. An increase in the price of carbon τ induces a reorganization of the energy mix towards less polluting energy sources. Since the cost of energy increases as a result, the emission intensity decreases. On the other hand, an increase in the price of one individual energy source p_s^e has an ambiguous effect on emission, as discussed in Appendix B.2.

Expression (7) can be used to obtain estimates of α and of $P(p^e,\tau;\eta,\theta)$.[13] Expressing emissions in terms of revenue shares rather than estimating the production function to obtain α is crucial for the empirical application as it solves two challenges in the identification of that parameter. First, it breaks the problem of simultaneity between total factor productivity (TFP) and emissions. In (11), the TFP term A appears in the dependent variable (inside Y) and does not need to be controlled for.[14] Similarly, output prices p^y are unobserved and, if they vary across firms, are potentially endogenous to inputs. Since they appear in the left hand side of (11), unobserved output prices are allowed to correlate with emissions.

3.2 The firm's investment location decision

We now model the international investment decision, introducing most of the notation used in the empirical analysis. A foreign investment consists of an installation of given productive capacity controlled by a parent firm, indexed by i. Each year t a parent firm can make a new foreign investment in each country j = 1, …., J. Let $\pi_{ijt}^* = 1$ denote the decision to make a new investment in country j and $\pi_{ijt}^* = 0$ otherwise. Following McGrattan and Prescott (2009), Burstein and Monge-Naranjo (2009) and Ramondo and Rodríguez-Clare (2013), we assume that the technology of the investing firm is transferred to the foreign investment. The parent firm observes prices in each available location and forms an expectation on the profits the investment will generate in the future. Let π_{ijt} denote the expected net present value of these profits and F_{ijt} the fixed costs of investing. The parent firm invests in every location that delivers a positive profit π_{ijt} net of fixed costs. That is:

$$\pi_{ijt}^* = \begin{cases} 1 \text{ if } \pi_{ijt} > F_{ijt} \\ 0 \text{ otherwise} \end{cases} \tag{8}$$

[13] First order conditions such as this one have been used extensively in the production function literature to estimate heterogeneous input elasticities (Hall, 1988; Grieco and McDevitt, 2016; Doraszelski and Jaumandreu, 2018).

[14] Methods exist to address the simultaneity problem (Olley and Pakes, 1996; Levinsohn and Petrin, 2003; Ackerberg et al., 2015), using a control function to separate A from the error term. In those models, however, no variation separately identifies A and α when both are firm-specific.

Notice that a firm can make as many investments as there are countries. The outside option for the firm is to not invest abroad at all, in which case we assume that the associated expected profits are zero.

The investment decision depends on the environmental policy in the following way. If the firm locates within the geographical scope of the EU ETS it faces carbon pricing and pays the associated compliance costs. At the same time, it expects to obtain free allowances in proportion to the capital invested. Let $e^*_{ijt} = \frac{E^*_{jt}}{p^y_{ijt}Y_{ijt}}$ denote the free allowances per unit of revenue that the firm receives in this case. The price of allowances τ_{jt} is common to all firms and takes value τ_t in countries covered by the EU ETS and 0 otherwise. Let $ETS_{ijt} = \tau_{jt}(e_{ijt} - e^*_{ijt})$ denote the market value of the net emissions generated by the investment per unit of revenue. The profit function can be generally parametrized as follows:

(9) $$\pi_{ijt} = \boldsymbol{Z}'_{ijt}\beta + \lambda_{it}ETS_{ijt} = \boldsymbol{Z}'_{ijt}\beta + \lambda_{it}\left[\tau_{jt}(e_{ijt} - e^*_{ijt})\right]$$

where $\boldsymbol{Z}_{ijt}$ is a vector of profit shifters. If the investment is located in a regulated country the profits the parent company expects to receive from the new foreign investment are affected by the EU ETS, with parameter λ_{it} representing the magnitude of this effect. A firm with a higher output elasticity to energy α can expect to have higher compliance costs under the EU ETS, everything else equal.

The measures e_{ijt} and e^*_{ijt} represent expectations of the firm and are therefore not directly observable. They are, however, correlated with the emission intensity and free allowances experienced by the parent firm, which are observed. Let e_{i0t} and e^*_{i0t} denote these measures, respectively. Both e_{ijt} and e_{i0t} are determined at the firm level by its technological endowment, i.e. by its output elasticity to energy α which can be used to relate the two measures. On the other hand, e^*_{ijt} relates to e^*_{i0t} through the EU ETS allowance allocation rules. We can then use data on e_{i0t} and e^*_{i0t}, which are observed, to infer e_{ijt} and e_{i0t}.

4. Data

The analysis combines firm level data from several sources. The final dataset contains information on investment decisions, balance sheet data on inputs and outputs and data on emissions and free allowances received. The covered firms are those subject to the EU ETS over the years 2005-2012. We complement firm-level data with country-level energy data, combining data from several sources. We describe the different sets of data hereafter.

Investment data. We obtain investment data from fDi Markets, an online database operated by fDi Intelligence, a division of the Financial Times Ltd.[15] The database collects information on cross-country investments of multinational companies, focusing on greenfield investments. A greenfield investment is defined as the construction of a brand-new plant or the expansion of an existing one. It therefore consists of an expansion of productive capacity. The data collected are based on investment announcements in media sources and company data; the information is updated daily and 90% of it is cross-referenced with company sources. The database contains precise information on the geographical origin and destination of the investment, as well as the amount of the capital investment.

Data on firms' inputs and output. Financial accounting data are obtained from Orbis, an online database maintained by Bureau van Dijk.[16] Orbis covers a vast number of companies worldwide and includes balance sheet data as well as profit and loss account data, that register revenues as well as expenditures for inputs.

EU ETS data. Data on emissions are contained in the publicly available database EU Transaction Log (EUTL, formerly known as CITL).[17] For each "account holder" (a firm), the EUTL contains the address of the holder, the verified emissions of each installation, the free allowances allocated, and the status of the account. For each year we know if the account was active and whether it was compliant. Out of the 9,263 (non-aircraft operator) account holders under the EU ETS, we find a matching name with Orbis for 8,047 accounts.

Energy data. The main source for energy price data is the International Energy Agency (IEA) Energy Prices and Taxes dataset.[18] It contains detailed data on the prices of several energy sources, covering all OECD countries and some selected non-OECD countries. We consider here the prices of oil (light fuel oil), gas (natural gas), electricity and coal (steam coal). All

[15] https://www.fdiintelligence.com/fdi-markets

[16] https://www.bvdinfo.com/en-gb/our-products/data/international/orbis

[17] https://ec.europa.eu/clima/ets/

[18] https://www.iea.org/data-and-statistics/data-product/oecd-energy-prices-and-taxes-quarterly

prices are expressed at constant U.S. dollars per unit of fuel and are harmonized across countries to account for different quality.[19]

Based on the above data sources we match the fDi Markets and the EUTL data using the name matching feature commercially provided by Bureau van Dijk on the Orbis platform. The results are verified on the basis of geographic and activity coherence (the only information available in all three datasets besides the name). We find a matching name in Orbis for 80% of the firms in the fDi Markets dataset and 87% of those in the EUTL. The total number of investments from firms covered by the EU ETS is 1,537 with a combined value of 139 billion euros. Investments are located in more than 50 countries, though some of the locations with fewer investments are aggregated. Table 1 provides details on number and value of investments by country, whereas Table 2 provides the same information by sector. The median investment is sizable (24 million Euro), but the dataset also contains smaller investments (around 150 000 Euro). The industries with more investments are automotive and chemicals. They are also the most important in terms of monetary size of investments, followed by the Coal, Oil and Natural Gas sector.

Table 1: Number and size of investments by location

	Number	Value (bn€)	% of FDI[1]
Austria	26	0.8	21.1
Belgium	55	3.6	15.6
Bulgaria*	19	1.5	
Czech Republic	13	0.7	8.0
France	74	3.3	8.6
Germany	39	5.1	11.9
Hungary	39	3.9	
Italy	11	0.5	1.3
Netherlands	11	2.8	5.5
Poland	58	5.8	18.7
Romania*	62	5.5	
Slovakia	25	5.9	
Spain	53	4.4	5.3
Sweden	19	0.9	1.9
UK	41	2.4	1.8
Total ETS countries	545	47.2	
Brazil	40	5.4	
Canada	24	2.5	2.2

[19] When available, we use information on after-tax prices for industrial consumers. This dataset is characterized by significant missing values (35% of annual prices are not available), especially for coal. We impute missing values using a reduced-form predictive model, detailed in Appendix D.

China	208	27.3	
India	112	6.9	
Indonesia	9	0.5	
Japan	12	0.5	3.7
Malaysia	14	0.8	
Mexico	36	4.9	6.3
Other Central Asia	6	0.6	
Other East Asia and Pacific	8	0.2	
Other Europe	45	3.2	
Other Latin America and Caribbeans	40	5.1	
Other Middle East	23	6.9	
Other North Africa	10	2.0	
Other Sub-Saharan Africa	14	0.4	
Russia	75	4.0	
Singapore	25	3.5	
South Africa	12	1.0	
South Korea	18	2.0	
Switzerland	12	0.6	1.9
Thailand	15	0.1	
Turkey	17	1.4	6.7
UAE	20	0.8	
Ukraine	17	0.6	
United States	167	10.7	1.6
Vietnam	13	0.3	
Total Non ETS countries	992	92.2	
Total	1537	139.4	

Notes: Investments by firms covered by EU ETS in the years 2005-2012. Bulgaria and Romania became EU members in 2007. Only the investments used for the empirical analysis included. [1] The last column compares the monetary value of the investments in the dataset with the total inward FDI value (source: OECD) in the manufacturing sector for OECD countries.

Table 2: Number and size of investments by industry

	Number	Value (bn€)
Aerospace & Defence	37	1.7
Alternative/Renewable energy	44	8.7
Automotive	427	46.2
Beverages	20	0.6
Biotechnology	12	0.3
Building & Construction Materials	89	7.3
Ceramics & Glass	47	1.8
Chemicals	331	28.3
Coal, Oil and Natural Gas	67	18.0
Consumer Products	33	0.7
Food & Tobacco	34	0.6
Industrial Machinery, Equipment & Tools	8	1.0

Med devices & Healthcare	30	0.5
Metals & Minerals	56	3.8
Paper, Printing & Packaging	46	6.3
Pharmaceuticals	79	3.0
Plastics	37	1.1
Rubber	84	7.4
Textiles	13	0.8
Transport (other)	22	0.6
Wood Products	11	0.4
Other	10	0.2
Total	1537	139.4

Notes: Investments by firms covered by EU ETS in the years 2005-2012. Only the investments used for the empirical analysis included. The category "Other" includes industries with less than 5 investments in the dataset.

Table 3 shows descriptive statistics on the firms included in the dataset. Firms differ in their emission intensity and the distribution is very skewed to the right: on average they emit 10 tons of CO_2 per thousand euro of revenues, but the median is much lower at 1.4 tons. Similarly, the expenditure on allowances, net of free allocation, is on average equal to 3% of total revenues, but the median expenditure is closer to 0.3%. In 24% of the cases a firm has received more free allowances than it has surrendered, thus benefiting from the EU ETS.

Table 3: Descriptive statistics

N = 4,194 firms	Mean	s.d.	p25	p50	p75
Emissions (kt)	976	7652	16.5	53.7	216
Free allowances (k)	379	2296	10.7	29.8	107
Regulated installations (n)	2.20	3.51	1.00	1.00	2.00
Emissions/Sales (tons/(k€)	10.3	42.5	0.31	1.42	6.59
Gross Value of Emissions/Sales	124	577	2.87	14.8	76
Net Value of Emissions/Sales (k€)	32.7	679	0.006	2.87	21.7
Revenues (M€)	701	5060	12.0	53.8	217
Cost of employees (M€)	85.5	707	1.41	6.28	26.2
Fixed Assets (M€)	574	5126	7.49	32.3	128

5. Empirical analysis

In this section we estimate the determinants of the foreign investment decisions. Emission intensity, e_{ijt}, and the free allowances received, e^*_{ijt} determine the compliance costs. These two measures are not observed for new investments but correlate with those associated to the activity of the parent firm, e_{i0t} and e^*_{i0t}, which are observed. Appendix C shows how firms investing in the EU ETS have higher emission intensities and lower free allowance received, providing preliminary evidence in favor of the model.

Even in the same industry, firms use energy to quite different extents. Thus, as a first step we recover firm-specific estimates of the technological parameter that determines this difference α. With this estimate at hand, we construct measures for e_{ijt} and e^*_{ijt}. Subsequently, we examine the extent to which this difference affects the investments decisions, estimating the empirical counterpart of (7).

Before proceeding we observe that the model has the advantage of allowing for a large choice set, comprised of all the J available countries, but this comes at the cost of two simplifying assumptions. First, the firm does not take into account how investing today will affect its future investments. Agglomeration effects can increase the profitability of sequential investments in the same location (Wagner and Timmins, 2009). Second, the firm does not form expectations on future prices and especially on the allowance price. As ignoring these dynamics can theoretically bias estimates, we provide evidence of the contrary in the robustness checks.

5.1 Estimation of emission intensities

In this section we estimate the determinants of emissions using domestic data (j = 0) following the theoretical model of Section 3. Let the vector of country-wide energy prices for the domestic country and the candidate locations be denoted by $p^e_{jt} = \{p^e_{oil,jt}, p^e_{ele,jt}, p^e_{gas,jt} p^e_{coal,jt}\}$. The cost of carbon is denoted by τ_{jt}. Let k denote the industry in which firm i operates. We estimate this empirical counterpart of (11) after taking logs:

$$(10) \qquad \log e_{i0t} = \log \alpha_i + \log P_k(p^e_{0t}, \tau_{0t}) + \epsilon_{i0t}$$

where ϵ_{i0t} is an iid disturbance. Here, we crucially let α_i to vary with the firm: in the empirical model this is an unobserved source of heterogeneity that we model as a firm fixed effect. The term $P_k(p^e_{0t}, \tau_{0t})$ is allowed to depend on the industry to capture industry-specific differences in η_k. Equation (10) makes clear that the data are domestic (j = 0), as said. After α_i is taken into account, $P_k(p^e_{0t}, \tau_{0t})$ explains the remaining difference in emission intensities, capturing the effect of energy prices and carbon prices the firm faces in its country of origin. Because of this term, e_{i0t} cannot be used directly as a measure of the firm's sensitivity to carbon leakage. Low emission intensities might be caused by high prices of energy (or low allowance prices), but production from an investment could be more polluting if located where energy is expensive (or allowances are cheap).

On the basis of the model laid out in Section 3, $P_k(p^e_{0t}, \tau_{0t})$ has a parametric form. Absent α_i, (10) could in principle be estimated parametrically, using standard non-linear techniques. However, if more generally $\alpha_i \neq \alpha_{i'}$, estimation is more complicated. The non- linearity of $P_k(p^e_{0t}, \tau_{0t})$ makes it impossible to proceed with the standard within estimator, which recovers the fixed effect by subtraction. We therefore estimate (10) using a semi non-parametric approach similar to Baltagi and Li (2002). We consider a power series approximation of (p^e_{0t}, τ_{0t}) choosing the precise specification through k-class cross validation.[20] As a data-driven model selection technique, cross validation helps address the risk of overfitting a polynomial, selecting the model that minimizes the loss due to the tradeoff between bias and variance of the estimates. Estimation then proceeds by standard within estimation. Proceeding this way also partially relaxes the assumption on the functional form adopted for energy production, which is not constrained by any parametric form in the empirical model.

Table 5 presents the estimates for the elasticity of the emission intensity to carbon and energy prices as in equation (10). Column 1 reports the results for an OLS regression, including year and industry intercept shifters. Column 2 is estimated including year and firm-specific fixed effects. Column 3 is the main specification, as it allows for industry-specific $P_k(p^e_{0t}, \tau_{0t})$, obtained interacting with industry dummies each price and their transformations. Column 4 also includes a country-specific slope coefficient for coal price, to control for the fact that the

[20] The power series we use includes all prices (in logs), their square, and their interactions, as well as year dummies. The details are discussed in Appendix D. Estimation then proceeds by standard within estimation. Since series estimators work by linear approximation, this solves the problem of estimating the fixed effects without resorting to stronger assumptions on the data generating process. Proceeding this way also partially relaxes the assumption on the functional form adopted for energy production, which is not constrained by any parametric form in the empirical model.

coal market is more regional than gas or oil. The results reported in the table are the averages taken across industries.

Table 5: Emission intensity elasticity to prices

	(1) OLS	(2) FE	(3) FE	(4) FE
ETS price	-1.295*** (0.145)	-1.432*** (0.082)	-1.473*** (0.085)	-1.478*** (0.082)
Oil price	0.147 (0.213)	-0.139 (0.122)	-0.136 (0.117)	-0.074 (0.116)
Electricity price	0.083 (0.109)	-0.092 (0.070)	-0.039 (0.067)	-0.059 (0.055)
Gas price	-0.071 (0.107)	0.094* (0.047)	0.043 (0.048)	0.048 (0.047)
Coal price	0.140 (0.085)	0.147** (0.056)	0.069 (0.048)	-0.079 (0.052)
No. observations	23661	23758	23661	23661
No. firms	4083	4093	4083	4083
Adjusted R^2 Within R^2	0.34	 0.50	 0.53	 0.53
year	Yes	Yes	Yes	Yes
country & industry fixed effects	Yes	No	No	No
firm fixed effects	No	Yes	Yes	Yes
industry slope	No	No	Yes	Yes
coal country slope	No	No	No	Yes

Notes: All prices are logged. Estimates are obtained by regressing the log of per-revenue emissions $\log e_{i0t}$ on a second-order series approximation of the carbon cost index $P_k(p^e_{0t}, \tau_{0t})$. Specification (1) is the OLS estimate, including year, country and industry fixed effects; specification (2) includes years and firm fixed effects; specification (3) also includes industry-specific elasticities: those reported are mean elasticities across industries; specification (4) also includes country-specific coefficient for coal: those reported are mean elasticities across industries and countries. Elasticities are estimated with the delta method. Standard error clustered at the firm-level in parenthesis. Three asterisks indicate a significance with $p < 0.001$.

The table shows that an increase in the price of carbon is associated with an elastic reduction in emissions, suggesting that firms do react to the policy. Energy prices elasticity are less precisely estimated, especially in the first two specifications. This could be due by the incapacity of firms to adjust quickly their energy mix or possibly to correlation between the prices.[21]

5.2 Construction of expected compliance costs

We now compute the expected compliance costs per unit of revenue $ETS_{ijt} = \tau_{jt}(e_{ijt} - e^*_{ijt})$, which is the variable of interest for the location decision model. For investments within the EU ETS, the median counterfactual compliance cost is 0.13 percentage points, the average is 1pct and its standard deviation is 0.43pct. For comparison, the observed expenditure share of emissions in the original data have a median of 0.15pct, average 1.26pct, and standard deviation 0.59pct, respectively. Since the price of allowances is zero outside of the EU ETS, $ETS_{ijt} = 0$ in this case.

Note that expected compliance costs are a constructed variable as free allowances and gross emissions are estimated as described hereafter.

Free Allowances. A new investment generates free allowances if it is located within the EU ETS, as discussed in Section 2. The amount of free allowances is calculated on the capacity installed. We estimate the amount of free allowances a firm would receive in this case with the following equation based on domestic data:

(11) $$E^*_{i0t} = b_k K_{i0t} + \nu_{i0t}$$

where K_{i0t} is the accounting value of fixed assets, reported by firm *i* in its balance sheet. This regression captures the between-industry differences in the way capital is accounted for allowance assignment. The coefficient b_k can be interpreted as the fraction of capital that is employed in emitting activities under the EU ETS.[22] The results are presented in Table 6.

Table 6: Free allowances per million euro of capital

	b_k	Standard error

[21] When differences in industries are taken into account by estimating industry-specific elasticities, not reported here, many are significant and have the expected sign.

[22] Instead of resorting to estimation, it would be in principle possible to calculate the allowances, given the sector benchmarks and the appropriate formula discussed in Section 2. However, data on volumetric capacity are not available. The coefficient b_k can be interpreted as the product of the benchmark times an estimated conversion factor from accounting capital to volumetric capacity.

Aerospace & Defense	11.8	4.1
Alternative Energy	1305.0	608.6
Automotive	10.9	3.5
Beverages	4.2	2.8
Building & Construction Materials	414.4	147.0
Business Services	34.6	40.5
Ceramics & Glass	378.2	45.4
Chemicals	110.9	30.2
Coal, Oil and Natural Gas	189.6	40.6
Consumer Products	42.2	0.8
Electronic Components	8.1	6.1
Food & Tobacco	121.1	51.4
Industrial Machinery, Equipment & Tools	273.8	167.0
Med devices & Healthcare	14.4	11.8
Metals & Minerals	48.7	50.5
Other (Combustion of fuels)	107.8	13.7
Paper, Printing & Packaging	110.3	31.6
Pharmaceuticals	3.7	1.7
Plastics	20.6	17.1
Real Estate	324.0	348.1
Rubber	177.9	26.5
Semiconductors	250.0	149.7
Software & IT services	203.4	125.3
Textiles	175.7	9.7
Transport (other)	0.8	0.6
Wood Products	111.4	80.8
No. of firms	4189	

Notes: The table reports estimates of free allowances assigned to firms as a function of capital installed. The first column reports the industry-specific coefficients and the second one its standard error, estimated by clustering them. Five industries with less than 10 firms have not been reported.

The results show wide variation across industries, where heavy polluting industries receive more free allowances per unit of physical capital and less polluting industries receive less. For example, the sector "Alternative energy producers" (mostly biomass electricity generators) receives 1,305 free allowances per million of fixed asset. Most of the physical capital in this industry is connected to power generation, which is eligible for free allowances. On the other hand, "Transport (other)", which includes mostly shipping and logistic companies, receives very few allowances per fixed assets million (0.8 per M€, or €10.4 if the price is €13).

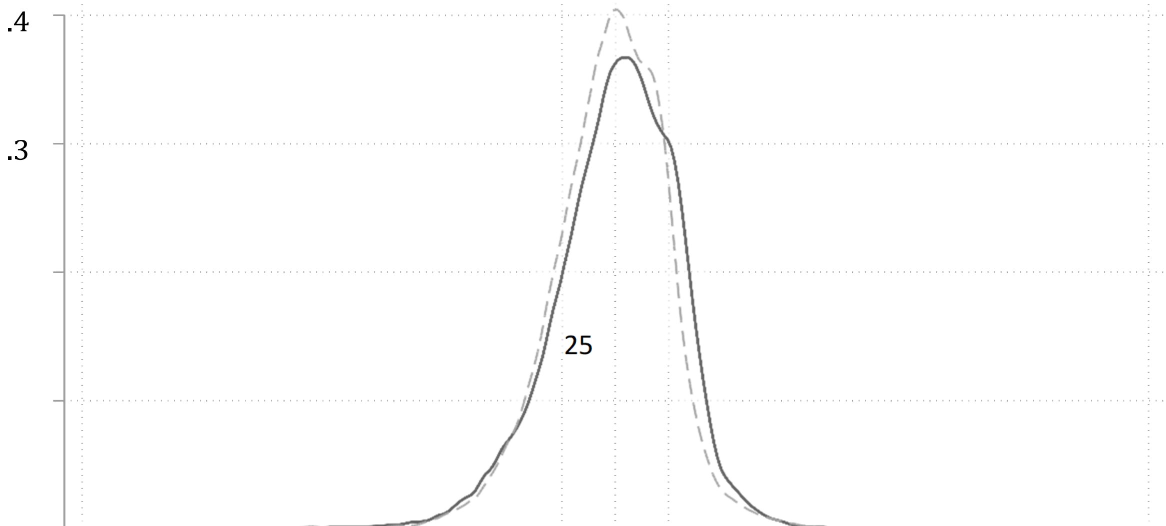
We use this information to obtain an estimate of free allowances for new investments $\hat{E}^{*}_{i0t} = \hat{b}_k K_{i0t}$ if the firm locates within the EU ETS. If the firm locates the investment outside the EU ETS, it receives zero free allowances.

<u>Gross Emissions</u>. The firm forms an expectation on how much its new investment is going to emit. These expectations are not observed, but they can be recovered using once again the condition derived in Section 3.1. As discussed, the emission intensity depends on the output elasticity to energy α_i and on the prices of carbon and energy through $P_k(p^e_{jt}, \tau_{jt})$. We construct an estimate for the expected emission intensity using:

$$\log e_{ijt} = \log \hat{\alpha}_i + \log \hat{P}_{kjt} \quad (12)$$

where $\hat{\alpha}_i$ is the estimate of α_i from (10). To obtain $\hat{P}_{kjt} = \hat{P}_k(p^e_{jt}, \tau_{jt})$ we form in-sample predictions using the energy prices of each possible destination. For this method to predict the right emissions per revenue, the technology of the firm needs not to depend on the country $\alpha_{ij} \neq \alpha_i$. Importantly, this conditional emission intensity allows for fuel switches (an effect captured in $\hat{P}_{kjt}$) or input substitution. Moreover, in Section 3.1 it was shown that, under a Cobb-Douglas production, per-revenue emissions are not affected by other factors, such as labor and capital prices and total factor productivity. This condition states that the process in which energy is transformed into output is the same in the headquarter and in the new plant. Focusing the analysis on greenfield investments, i.e. investments in new productive capacity, excludes mergers and acquisitions and vertical investments in non-productive subsidiaries and reinforces this assumption. In addition, given the context of mature and heavy manufacturing firms and energy producers, this assumption seems credible. We visualize the distribution of observed emission intensities e_{i0t} and estimated expected emission intensities e_{ijt} in Figure 1.

Figure 1: Expected and observed emission intensity



.2

.1

0

-10 -1 0 1 10

Notes: Kernel density of the expected emission intensities. The solid line represents the density of the expected emission intensities, predicted using equation (10). The dashed line represents the emission intensities observed domestically for the investing firm. The emission intensities on the x-axis are expressed in $\log_{10}$ tons of CO_2 per thousand euros of revenues. The graph is cropped for readability (0.13% observations dropped).

5.3 Estimation of the location decision model

We consider the following empirical counterpart of equation (13):

$$\pi_{ijt} = \boldsymbol{Z}_j'\beta + \lambda ETS_j + \mu_j + \varepsilon_{ijt} \qquad (13)$$

where ε_{ijt} is an i.i.d. unobserved profit component. The vector $\boldsymbol{Z}_j$ contains control variables typically used in the trade literature on gravity equations (Anderson, 2011). Specifically, it includes two measures of distance: geographical distance and a measure of cultural distance. For geographical distance, we calculate the distance in kilometers from the centroid of the country of origin to the centroid of the country of destination. For cultural distance, a dummy is used equal to one if the two countries share a common official language. Secondly, it includes economic variables that control for economic activity such as GDP, GDP per capita and total exports. All these variables are in logs. Finally, it includes the (log of) inward foreign direct investment of the previous year. This variable serves the purpose of controlling for aggregation effects in addition to proxying general attractiveness (Wagner and Timmins, 2009). The variable is lagged by one year to address possible simultaneity problems with the dependent variable. We follow the tradition in the trade literature of including country-specific fixed effects (Eaton and Kortum, 2002; Head and Ries, 2008; De Sousa and Lochard, 2011): they are particularly important as they capture, for example, the impact of other location-specific environmental policies as long as they are time-invariant.[23] Note that all the

[23] We experimented with a richer set of fixed effects, including industry-by-location and time-by-location fixed effects but the sample size impose excessive requirements on the data. Results are qualitatively similar.

additive shifters to the investment profit that are not alternative-*j* specific, such as year-by-firm fixed effects, are implicitly controlled for. Since only differences in profits between locations matter their contribution to profits are not identified. Equation (14) cannot be directly estimated as π_{ijt} is not observed; only the final investment decisions are. Under the assumption that the unobserved profit component is random with an Extreme Value type-I distribution, we can use the conditional logit approach of McFadden (1973, 1975) originally developed for random utility models.[24] In this approach, each choice situation for each firm is a separate observation. We can express the conditional probability of firm *i* at time *t* taking a location decision *j* in the following way:

(14) $$P_{ijt} = \frac{exp\left(\boldsymbol{Z}'_j\beta + \lambda ETS_j + \mu_j\right)}{\sum_{j'} exp\left(\boldsymbol{Z}'_j\beta + \lambda ETS_j + \mu_j\right)}$$

and form the corresponding maximum likelihood as:

(15) $$L(\beta, \lambda, \varepsilon) = \prod_{i=1}^{N} \prod_{j=0}^{42} \prod_{t=2005}^{2012} \left(P_{ijt}\right)^{\pi^*_{ijt}}$$

where β, λ and ε are vectors of parameters to be estimated and π^* is the investment choice as defined in (8). Results from the maximum likelihood estimation are reported in Table 7.

Table 7: Multinomial logit estimates of the investment decision model

Probability of investing in j	(1)	(2)	(3)
ETS_{ijt}	-9.005*** (3.403)		
$\tau_{jt}e_{ijt}$		-9.789*** (1.574)	
$\overline{ETS}_{kjt}$			-0.551 (0.426)

[24] This approach is also a natural generalization of the Poisson approach often used in the investment location literature. Papers in that literature start from a similar behavioral model and aggregate the logit probabilities at the country or country-industry level. Since aggregated logits distribute Poisson, estimation proceeds by Poisson maximum likelihood, which is computationally advantageous because it reduces the dimensionality of the problem. The drawback is that explicit within-industry heterogeneity, which is precisely the interest of the present paper, is lost in the aggregation and can at most be recovered by strong distributional assumptions (i.e. assuming that it is a random effect or parameter of a known distribution).

Distance	-0.531***	-0.531***	-0.570***
	(0.148)	(0.060)	(0.060)
Shared language	0.527***	0.530***	0.474**
	(0.242)	(0.145)	(0.142)
GDP	1.165***	1.165***	1.220***
	(0.248)	(0.090)	(0.086)
GDP per capita	0.015***	0.015***	0.011***
	(0.016)	(0.003)	(0.003)
Exports	-2.234***	-2.236***	-2.278***
	(0.437)	(0.110)	(0.103)
Incoming FDI	0.147***	0.148***	0.115***
	(0.057)	(0.034)	(0.030)
No. observations	953598	953598	1031022
No. choices	23285	23285	24624
No. firms	4083	4083	4089
Location fixed effects	Yes	Yes	Yes

Notes: The table reports coefficients from a multinomial (conditional) logit estimation. The dependent variable is the probability of investing in a certain location. A negative coefficient means that higher values of the variable are associated with a lower probability of investing. In round brackets block-bootstrapped (200 repetitions) standard error for model (1) and standard errors clustered at the firm level for model (2) and (3). GDP, exports and FDI are logged and expressed in M€; GDP per capita is in thousand €; distance in thousand kilometers. Three (resp. two) asterisks indicate a significance with $p < 0.001$ (resp. 0.01).

Column 1 reports the results from the main specification. A negative coefficient of ETS_{ijt} is associated with a lower probability for the firm to locate its investments within the EU ETS. As a reminder, ETS_{ijt} is higher if the firm is more emission intensive or the allowance price is higher and is lower if the free allowances allocated to the firm are lower. However, the coefficients in the table cannot be directly interpreted. To give a sense of the results we can compare the coefficient of ETS_{ijt} to those of the other covariates. A standard deviation increase from the mean in ETS_{ijt} is equal to a 28% increase in the emission expenditure on revenues. Column 2 reports the results from a specification using as variable of interest only $\tau_{jt}e_{ijt}$, i.e. it ignores the measure estimated for e^{*}_{ijt}. The estimated coefficient is similar to that of ETS_{ijt}. This suggests that the expected compliance costs $\tau_{jt}e_{ijt}$ drive the result, while free allowances bear less importance on the investment location decision. Column 3 repeats the exercise using an industry-wide measure for ETS_{ijt}, $\overline{ETS}_{kjt}$, constructed using $\bar{\alpha}_k$, the median output elasticity to energy in an industry, instead of the firm-specific α_i. This specification mimics the problem of using industry aggregates instead of firm-specific values for emission intensity. When firm heterogeneity is ignored, the estimated effects of carbon pricing on investments are not statistically different from zero.

We note that the variable of interest ETS_{ijt} is a generated regressor, so that standard inference is invalid. A two-stage estimation procedure delivers consistent estimates, but the standard errors need to be adjusted to take the first stage into account. We use a bootstrap procedure to recover an empirical distribution of λ which can be used for testing. To allow for within-firm correlation of errors, we block-bootstrap at the firm level, constructing estimates $ETS_{ijt}(r)$ for each repetition r and re-estimating the model to obtain $\lambda(r)$. Quantiles of $\lambda(r)$ can be used to construct confidence intervals. The bootstrapped standard errors used here are larger than the naive ones, e.g. $\widehat{s.e.}_{boot}(\lambda) = 3.4$, while $\widehat{s.e.}_{naive}(\lambda) = 1.5$ for the model in column (1).

6. Policy implications

To help appreciate the results presented above, especially the magnitude of the investments diverted by carbon pricing, we consider here two policy exercises: (1) a higher price of carbon resulting from a tighter initial supply of allowances; (2) no free allowances distributed to firms.

Increase in the allowance price. We first consider the effects on investments of a tighter supply of allowances leading to a constant price of €30 per allowance. The EU ETS allowance prices have been lower than most estimates of the social cost of carbon, including the most conservative ones.[25] Arguably, this was caused by an excessive supply of allowances. To address this problem, the carbon targets (and consequently the allowances supply) have been progressively reduced and the allowance price has increased as a result. Here, we estimate

[25] See Tol (2011) for a review.

the capital and emissions that would have been displaced in the period 2005- 2012 by a further increase in this price.

We model the price increase as a left shift of the allowances supply curve along the demand curve. The average price of allowances over the period was €13.52.[26] We consider an increase to €30, equal to an average increase by 122%. Since supply is fixed in advance, it is a perfectly inelastic curve. The other prices are held constant.[27] For each firm, we predict the new quantity of allowances demanded per unit of revenue using (8). We then predict the outcome of the model using the new values for ETS_{ijt}. As a result of the price increase, the results suggest that firms' emission intensity would have decreased by 57%.[28]

Figure 2 shows the changes in investments implied by the model. The results are presented respectively for the firms classified as not exempted from auctioning, the firms exempted from auctioning and the not classified ones.[29] The exempted firms are those deemed at risk of carbon leakage by the regulation.

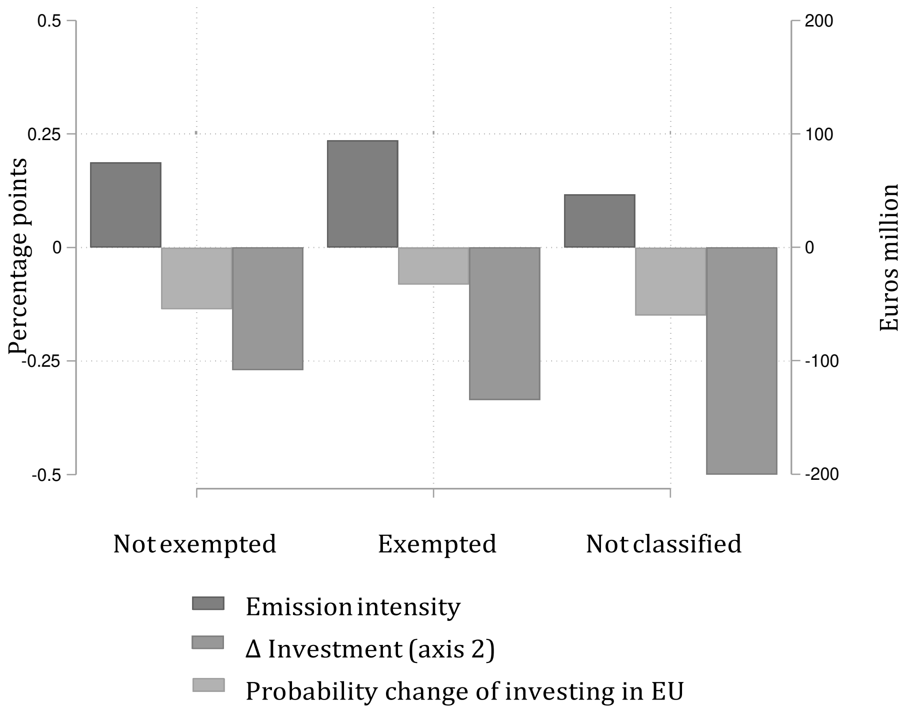
Figure 2: Effects on investments of an allowance price increase to €30

[26] The lowest price was €0.72 in 2007, while the highest price was €22.67 in 2008.

[27] Importantly, the price of energy is held fixed or, in other words, we implicitly assume no pass-through of higher costs from energy producers to consumers. This assumption seems justified for fuels other than electricity since producers are mostly located outside of the EU ETS. However, some pass-through can be expected for electricity producers (Fabra and Reguant, 2014). If electricity prices increase because of pass-through, the effect estimated here is underestimated for manufacturers and overestimated for energy producers.

[28] This decrease is quite high and probably due to the linear extrapolation of the demand elasticities which overestimates the reaction of the firm. To obviate this problem, we repeated the exercise keeping the emission intensities fixed, modeling the price increase as a proportional upward shift of firms demand for allowances, rather than a supply shift. The effect is an increase of the averted investments, as the expenditure share becomes larger, but stays reasonably close to the results reported here.

[29] The number of firms belonging to the three categories is 1,110, 1,730 and 1,362 respectively. See Appendix A for details on this classification.



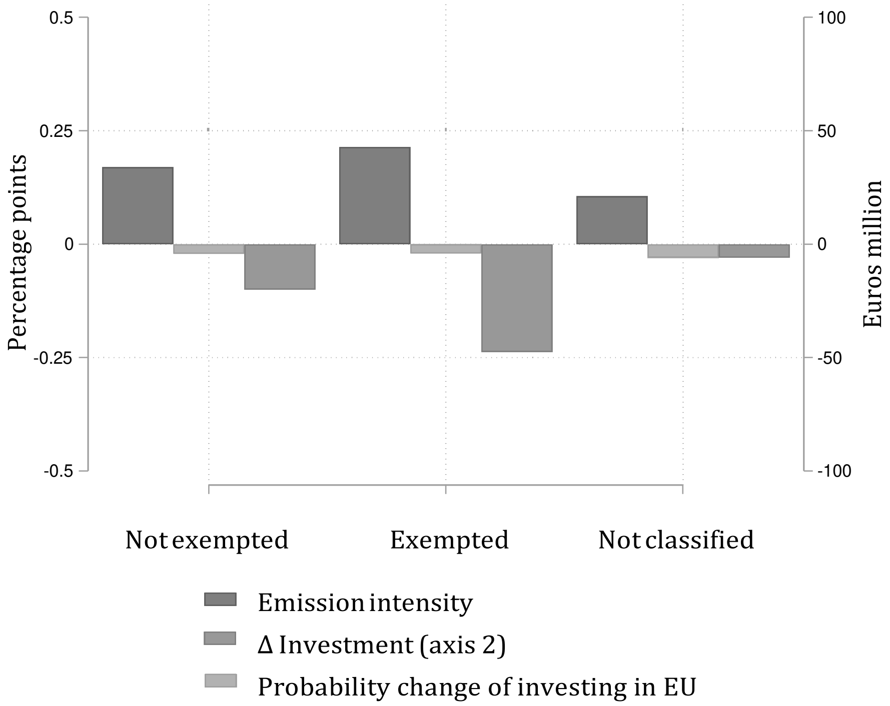
Notes: Effects on investments of an allowance price increase to €30 over the period 2005-2012 for firms not exempted and exempted from auctioning and not classified. The emission intensities reported are those associated with activity in the lost investment. The probability change is the average decrease in the probability the firm invests in the EU ETS area, conditional on investing internationally.

The figure reports three values. The leftmost bar in each category shows the average emission intensity associated with the lost investments. This calculated activity from exempted firms is on average more polluting than those from not exempted firms, as expected from the definition of exempted industries discussed in Section 2: their emission intensity is 25% higher. The middle bar shows the change in the probability of investing in a EU country, conditional on making any investment at all, averaged by category. The probability of investing decreases by 0.1 percentage points, more for not exempted firms (-0.14 percentage points) than for exempted firms (-0.08). The right bar shows the aggregate loss in investments by category. An allowance price increase to €30 is associated with an expected loss of investment of 443 M€. Of these, 108 million are due to not exempted firms and 134 million to exempted firms.

Zero free allowances. To evaluate the contribution of free allowance on investments we consider a scenario in which firms do not receive free allowances. This is done by imposing

$e^*_{ijt} = 0$ when calculating ETS_{ijt}. We then predict the investments implied by the model in this case and compare the result with the baseline data. Figure 3 shows the results.

Figure 3: Effects on investments reducing to zero the free allowances



Notes: Effects on investments reducing to zero the free allowances, over the period 2005-2012 for firms not exempted and exempted from auctioning and not classified. The emission intensities reported are those associated with activity in the lost investment. The probability change is the average decrease in the probability the firm invests in the EU ETS area, conditional on investing internationally.

The emission intensities of the investments are 26% higher for exempted firms than for not exempted firms. Reducing free allowances to zero has a small and very similar effect on the probability of investing in the EU for both categories of firms (-0.2 percentage points). These two measures should be implicitly targeted by the classification rules into exempted and not exempted firms. To be efficient, compensations should target those firms that have more elastic investments to carbon pricing and have more emission intensive investments (Martin et al., 2014b). Even ignoring the magnitude of the effects in place, this exercise shows that the classification criterion fails on the first objective and only partially succeeds on the second. The rightmost column for each category in the graph shows the effect on the expected investments in the EU ETS area. Reducing to zero the free allowances is associated with an expected loss of 73 M€, equal to a -0.17% reduction in investments in the area with respect to the full sample. To give an idea of the magnitude of this loss with respect to the compensation scheme, the free allowances distributed over the period were around 2 billion per year, with an average allowance price of €13.52. Although not all these allowances were handed as compensation, the associated retained investments are remarkably small.

7. Robustness checks

An assumption of the model is that current prices are a good reflection of the firm's expectation on future prices. On this basis, one-period profits represented a good proxy for net present profits. Firms might, however, anticipate future events that are not captured by current prices. This fact is especially problematic if this happens for the allowance price τ_t as this is a key component of the variable of interest, ETS_{ijt}. To take explicitly into account this problem we look at future contract data for the EUAs.[30] These future contracts can be used by the firm to insure against future fluctuations in the allowance price. Their price can therefore be interpreted as the market's expectation. These prices correlate very strongly with the allowances spot price, suggesting that the latter incorporates fairly well expectations.[31]

To formally test the role of expectations for the investment location decision, we calculated the expected compliance costs from carbon pricing using the price of the future contracts. Denote with $E(ETS_{ijt+s})$ these costs where s = {1,...,5} represent a delivery date 1 to 5 years ahead. Results are presented in Column 1 of Table 8.

Table 8: Robustness checks

Probability of investing in j	(1)	(2)	(3)
ETS_{ijt}	-9.575***	-6.707***	
	(1.482)	(1.287)	
$E(ETS_{ijt+s})$	0.385		

[30] EEX CFI ICE future contract data. Source: Thomson Reuters.

[31] One relevant exception are future contracts on allowances for the second phase of the EU ETS, exchanged during the first phase. Because bankability was not allowed between those two phases, the two underlying assets were factually different.

	(0.394)		
$E(ETS_{ijt+s})$	-0.094		
	(0.670)		
$E(ETS_{ijt+s})$	10.44		
	(14.021)		
$E(ETS_{ijt+s})$	-12.89		
	(25.406)		
$E(ETS_{ijt+s})$	2.251		
	(11.700)		
ETS_{ijt} × Phase I			-4.875**
			(1.698)
ETS_{ijt} × Phase II			-13.77***
			(2.167)
Past investment in j		4.884***	
		(0.072)	
N	953598	953598	953598
Choices	23285	23285	23285
Firms	4083	4083	4083
Location fixed effects	Yes	Yes	Yes
Covariates $(\boldsymbol{Z}_j)$	Yes	Yes	Yes

Notes: The table reports coefficients from a multinomial (conditional) logit estimation. The dependent variable is the probability of investing in a certain location. Standard errors clustered at the firm level for model in columns (2) and (3) in parentheses. Three (resp. two) asterisks indicate a significance with $p < 0.001$ (resp. 0.01).

Column 1 of the table shows that the main result is not affected and none of these variables are statistically significant. This is because of the strong correlation between the future contract prices and the spot price.

A second assumption of the model was that the investment decision is memory-less. In particular, the firm that decides where to locate its investment does not take into account whether or not it has invested in the same country in the past. This fact potentially ignores congestion or agglomeration effects as well as an unobserved preference of the firm for that country. To address this problem, we add a dummy variable that captures whether the firm has invested in the country before. Column 2 in Table 10 shows that the coefficient for this variable takes on a positive and significant value, suggesting either agglomeration effects or unobserved time-persistent preference of the firm for the country. The coefficient for ETS_{ijt} decreases a little, thus not affecting the results discussed so far.

Finally, we consider a more flexible specification for λ, allowing it to vary over the two EU ETS trading periods considered in this paper. We do so by interacting the variable ETS_{ijt} with a dummy variable for the second phase. Recall that the two phases had slightly different rules, as discussed in Section 2. Moreover, during the second phase the European Commission reinforced its intention to continue and strengthen the carbon pricing scheme. Column 3 in Table 6 shows results in line with this interpretation, with a coefficient for ETS_{ijt} in the second phase larger than that of the first phase.

6. Summary and Conclusion

The risk of carbon leakage contributes to timid climate change policies. The fear of hampering risk competitiveness with a strict regulation is compounded by that of falling short of reducing global emissions. Compensations in the form of free allowances are an attractive economic instrument to address this problem, because they do not hinder their efficient final allocation. But mostly important, they are politically appealing as they demand no disbursement by firms. Therefore, generous compensations schemes have been adopted in most carbon pricing schemes, without a critical assessment of whether they were effective, or needed.

In this paper we have provided this assessment by estimating the effect of the EU carbon pricing on international investments. To this end, we have used detailed data on firm-level emissions and investment decisions.

Absent detailed firm-level information, both academic research and policy makers have relied on industry-wide aggregates for evaluating carbon leakage and select the firms to compensate. This paper has taken a different approach, on the ground that firms are very heterogeneous within industries in their emission intensities. We exploited the data richness available for firms under the EU ETS and a novel dataset on greenfield investments to provide a finer characterization of the firms' emission patterns in relation with their investment location decisions. We have argued that the emissions from the investing company can be used to infer the expected compliance costs of the investment due to carbon pricing. We have used these estimated compliance costs in a model of investment location decisions to evaluate the effect of the EU ETS on the probability of firms to invest within Europe.

The expected compliance costs are not observed. The emissions of the parent company could be used to proxy for them, but those emissions are naturally endogenous to allowance prices. To address this issue, we have leveraged a theoretical model of the firm's production choices, which delivers an estimable condition between emissions and allowance and energy prices. We showed that a key determinant of this condition is the output elasticity to energy: a technological parameter that can be estimated from the first order condition of the firm. If the investing firm and the new plant share this same technology, this parameter can be used as the basis to infer the emission intensity of the new investment.

The findings point in the direction of a statistical effect of carbon pricing on investment location decisions. Interestingly, this effect disappears when we used industry aggregates instead of firm-level measures, reinforcing this paper's argument on the importance of firms' heterogeneity. However, we show that this effect is economically small. For example, an increase in the price of carbon to €30 is associated with a loss of 443 M€ over 7 years, or a reduction of -0.9%. Similarly, we show that the allocation of free allowances has contributed to attract 79 M€ in investments, vis-à-vis a very generous scheme.

We also provide evidence that the EU ETS classification rule for compensated firms misses partially its objective. Compensated firms are not more nor less respondent to carbon pricing than non-compensated firms, despite the fact that targeting more elastic firms would help reducing the size of the compensation scheme.

This paper contributes to the policy discussion on carbon markets in several ways. First, it stresses the importance of micro data for evaluating them and provides an easily generalizable framework to treat them. Second, it puts in perspective the risk of carbon leakage: it does not dismiss the possibility that firms react to environmental policies locating activity elsewhere, but it suggests that this is a more remote possibility than previous evidence suggested. Finally, it provides a basis to discuss the future of compensation schemes for carbon leakage, not only in the EU ETS, which has entered its fourth phase, but also in other carbon markets over the world.

References

Ackerberg, D.A., Caves, K., Frazer, G., 2015. Identification properties of recent production function estimators. Econometrica 83(6): 2411–2451.

Aichele, R., Felbermayr, G., 2015. Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. Review of Economics and Statistics 97(1): 104–115.

Aldy, J.E., Pizer, W.A., 2015. The competitiveness impacts of climate change mitigation policies. Journal of the Association of Environmental and Resource Economists 2(4): 565–595.

Anderson, J.E., 2011. The gravity model. Annual Review of Economics 3(1): 133–160.

Baltagi, B.H., Li, D., 2002. Series estimation of partially linear panel data models with fixed effects. Annals of economics and finance 3(1): 103–116.

Borghesi, S., Franco, C., Marin, G., 2020. Outward foreign direct investments patterns of Italian firms in the EU ETS. The Scandinavian Journal of Economics122(1): 219-256.

Brunnermeier, S.B., Levinson, A., 2004. Examining the evidence on environmental regulations and industry location. The Journal of Environment & Development 13(1): 6–41.

Burstein, A.T., Monge-Naranjo, A., 2009. Foreign know-how, firm control, and the income of developing countries. The Quarterly Journal of Economics 124(1): 149–195.

Bushnell, J.B., Chong, H., Mansur, E.T., 2013. Profiting from regulation: Evidence from the European carbon market. American Economic Journal: Economic Policy 5(4): 78–106.

Calel, R., Dechezleprêtre, A., 2016. Environmental policy and directed technological change: Evidence from the European carbon market. Review of economics and statistics 98(1): 173–191.

Carbone, J. C., Rivers, N., 2017. The impacts of unilateral climate policy on competitiveness: evidence from computable general equilibrium models. Review of Environmental Economics and Policy 11(1): 24–42.

Cludius, J., de Bruyn, S., Schumacher, K., Vergeer, R., 2020. Ex-post investigation of cost pass-through in the EU ETS - an analysis for six industry sectors. Energy Economics 91, 104883.

Colmer, J., Martin, R., Muûls, M., Wagner, U.J., 2022. Does pricing carbon mitigate climate change? Firm-level evidence from the European Union Emissions Trading Scheme. CEPR Discussion Paper N. DP16982.

Commins, N., Lyons, S., Schiffbauer, M., Tol, R.S.J., 2011. Climate policy & corporate behavior.

The Energy Journal: 51–68.

Copeland, B.R., 2008. The Pollution Haven Hypothesis. In: K.P. Gallagher (ed.), Handbook on Trade and the Environment. London: Edward Elgar Publishing, 60–70.

Copeland, B.R., Taylor, M.S., 2004. Trade, growth, and the environment. Journal of Economic literature 42(1): 7–71.

Copeland, B.R., Taylor, M.S., 2005. Trade and the environment: Theory and evidence. Princeton University Press.

D'Arcangelo, F. M., Pavan, G., Calligaris, S., 2022. The impact of the European carbon market on firm productivity: Evidence from Italian manufacturing firms. Fondazione Eni Enrico Mattei working Paper N. 024.2022.

De Bruyn, S.M., Vergeer, R., Schep, E., Hoen, M.'t, Korteland, M., Cludius, J., Schumacher, K., Zell-Ziegler, C., Healy, S., 2015. Ex-post investigation of cost pass-through in the EU ETS. European Commission.

De Sousa, J., Lochard, J., 2011. Does the single currency affect foreign direct investment? The Scandinavian Journal of Economics 113(3): 553–578.

Dechezleprêtre, A., Sato, M., 2017. The impacts of environmental regulations on competitiveness. Review of Environmental Economics and Policy 11(2): 183–206.

Dechezleprêtre, A., Gennaioli, C., Martin, R., Muûls, M., Stoerk, T., 2022. Searching for carbon leaks in multinational companies. Journal of Environmental Economics and Management 112: 102601.

Doraszelski, U., Jaumandreu, J., 2018. Measuring the bias of technological change. Journal of Political Economy 126(3): 1027–1084.

Eaton, J., Kortum, S., 2002. Technology, geography, and trade. Econometrica 70(5): 1741–1779.

Ellerman, A.D., Marcantonini, C., Zaklan, A., 2016. The European Union emissions trading system: ten years and counting. Review of Environmental Economics and Policy 10(1): 89–107.

Ellerman, A.D., McGuinness, M., 2008. CO2 abatement in the UK power sector: Evidence from the EU ETS trial period. MIT-CEEPR Working Paper N. 2008-010.

European Commission, 2015. Study on the impacts on low carbon actions and investments of the installations falling under the EU Emissions Trading System (EU ETS). Final Report.

Flues, F., van Dender, K., 2017. Permit allocation rules and investment incentives in emissions trading systems. OECD Taxation Working Paper N. 33.

Fowlie, M., Reguant, M., 2018. Challenges in the measurement of leakage risk. AEA Papers and Proceedings 108: 124–129.

Fowlie, M., Reguant, M., Ryan, S., 2016. Measuring leakage risk. California Air Resources Board Technical Report.

Grieco, P.L.E., McDevitt, R.C., 2016. Productivity and quality in health care: Evidence from the dialysis industry. The Review of Economic Studies 84(3): 1071– 1105.

Hall, R.E., 1988. The relation between price and marginal cost in us industry. Journal of political Economy 96(5): 921–947.

Head, K., Ries, J., 2008. FDI as an outcome of the market for corporate control: Theory and evidence. Journal of International Economics 74(1): 2–20.

Jaffe, A. B., Peterson, S.R., Portney, P.R., Stavins, R.N., 1995. Environmental regulation and the competitiveness of US manufacturing: what does the evidence tell us? Journal of Economic literature 33(1): 132–163.

Jaraité, J., Di Maria, C., 2012. Efficiency, productivity and environmental policy: a case study of power generation in the EU. Energy Economics 34(5): 1557–1568.

Jeppesen, T., List, J.A., Folmer, H., 2002. Environmental regulations and new plant location decisions: evidence from a meta-analysis. Journal of Regional Science 42(1): 19–49.

Keller, W., Levinson, A., 2002. Pollution abatement costs and foreign direct investment inflows to US states. Review of Economics and Statistics 84(4): 691–703.

Koch, N., Basse Mama, H., 2019. Does the EU Emissions Trading System induce investment leakage? Evidence from German multinational firms. Energy Economics 81(C): 479–492.

Levinsohn, J., Petrin, A., 2003. Estimating production functions using inputs to control for unobservables. The Review of Economic Studies 70(2): 317–341.

List, J.A., Co, C.Y., 2000. The effects of environmental regulations on foreign direct investment. Journal of Environmental Economics and Management 40(1): 1–20.

List, J.A., McHone. W.W., Millimet, D.L., 2004. Effects of environmental regulation on foreign and domestic plant births: is there a home field advantage? Journal of Urban Economics 56(2): 303–326.

List, J.A., Millimet, D.L., Fredriksson, P.G., McHone, W.W., 2003. Effects of environmental regulations on manufacturing plant births: evidence from a propensity score matching estimator. Review of Economics and Statistics 85(4): 944–952.

Lyubich, E., Shapiro, J., Walker, R., 2018. Regulating mismeasured pollution: Implications of firm heterogeneity for environmental policy. AEA Papers and Proceedings 108: 136–142.

Martin, R., Muûls, M., De Preux, L.B., Wagner, U.J., 2014a. Industry compensation under relocation risk: A firm-level analysis of the eu emissions trading scheme. American Economic Review 104(8): 2482–2508.

Martin, R., Muûls, M., De Preux, L.B., Wagner, U.J., 2014b. On the empirical content of carbon leakage criteria in the EU emissions trading scheme. Ecological Economics 105: 78–88.

Martin, R., Muûls, M., Wagner, U.J., 2016. The impact of the European Union Emissions Trading Scheme on regulated firms: What is the evidence after ten years? Review of environmental economics and policy 10(1): 129–148.

McFadden, D., 1973. Conditional Logit Analysis of Qualitative Choice Behavior. In: Frontiers in Econometrics (P.Zarembka ed.). New York: Academic Press, 105-142.

McFadden, D., 1975. The revealed preferences of a government bureaucracy: Theory. The Bell Journal of Economics 6(2): 401-416.

McGrattan, E.R., Prescott, E.C., 2009. Openness, technology capital, and development. Journal of Economic Theory 144(6): 2454–2476.

Naegele, H., Zaklan, A., 2019. Does the EU ETS cause carbon leakage in European manufacturing? Journal of Environmental Economics and Management 93: 125–147.

Olley, G., Pakes, A., 1996. The dynamics of productivity in the telecommunications equipment industry. Econometrica 64(6): 1263–1297.

Petrick, S., Wagner, U.J., 2014. The impact of carbon trading on industry: Evidence from german manufacturing firms. Kiel Working Paper N.1912.

Ramondo, N., Rodríguez-Clare, A., 2013. Trade, multinational production, and the gains from openness. Journal of Political Economy 121(2): 273–322.

Saussay, A., Sato, M., 2018. The impacts of energy prices on industrial foreign investment location: evidence from global firm level data. Grantham Research Institute on Climate Change and the Environment Working Paper N. 311.

Tol, R.S.J., 2011. The social cost of carbon. Annual Review of Resource Economics 3(1): 419–443.

Veith, S., Werner, J.R., Zimmermann, J., 2009. Capital market response to emission rights returns: Evidence from the European power sector. Energy economics 31(4): 605–613.

Verde, S., 2020. The impact of the eu emissions trading system on competitiveness and carbon leakage: the econometric evidence. Journal of Economic Surveys 34(2): 320–343.

Verde, S., Teixidó, J., Marcantonini, C., Labandeira, X., 2020. Free allocation rules in the EU Emissions Trading System: What does the empirical literature show? Climate Policy 19(4): 439-452.

Wagner, U. J., Muûls, M., Martin, R., Colmer, J., 2014. The causal effects of the European Union Emissions Trading Scheme: Evidence from French manufacturing plants. Presented at the Fifth World Congress of Environmental and Resources Economists.

Wagner, U. J., Timmins, C.D., 2009. Agglomeration effects in foreign direct investment and the pollution haven hypothesis. Environmental and Resource Economics 43(2): 231–256.

Xing, Y., Kolstad, C.D., 2002. Do lax environmental regulations attract foreign investment? Environmental and Resource Economics 21(1): 1–22.

Appendix

A. Firms at risk of carbon leakage

Precise information on whether a firm receives compensation for carbon leakage is not readily available. To obtain it, we consider the observed allocation of free allowances in conjunction with the regulation. The regulation states that the free allocation is to be progressively phased out. To that end, a linear reduction factor is applied every year from 2013 to the starting value of allocated allowances. On the other hand, no reduction factor is applied to protected firms. In practice, the free allowances have been reduced by -10.5% in non-protected industries, with small differences across industries due to the definition of industry benchmarks. Protected industries have experienced a reduction of about -1.7%. Since the difference is quite sharp, it is possible to use the free allowance data from 2013 to classify firms in one of the two categories by looking at the reduction in free allowances. We classify as “not exempted” (from auctioning) those firms that have experienced a reduction in free allowances between -8% and -13% and as “exempted” those firms that have experienced a reduction between -1% and -3%. Firms that undergo substantial changes in capacity, either increasing it or decreasing it, are allocated a different amount of allowances. When this happens for more than one year we opt for the most conservative approach and do not classify them. Table A.1 shows the number of firms ever active in the EU ETS and their classification, as well as the sum of associated emissions and allowances for three selected years.

It is possible to use this classification to estimate what amount of the free allowances is left as compensation, by calculating what the allowances would have been, if the reduction factor would have been increased equally for exempted and not-exempted firms. We take free allowances of exempted firms and apply the same reduction factor that applies to non exempted firms. This is done in Table A.2.

Table A.1: Classification of firms by risk of carbon leakage according to the EU ETS definition

Year	Classification	No. firms	Emissions (%)	Free allocations
2005	Not classified	1723	25%	425
	Not exempted	1370	40%	782
	Exempted	2069	35%	723
2009	Not classified	1607	23%	356
	Not exempted	1586	40%	659
	Exempted	2421	37%	782
2012	Not classified	1425	22%	374
	Not exempted	1674	41%	711

	Exempted	2493	37%	810
2017	Not classified	730	18%	19
	Not exempted	1803	40%	115
	Exempted	2988	42%	598

Notes: Classification of firms by risk of carbon leakage according to the EU ETS definition. The classification is based on the observed changes in the free allowances allocation between the years from 2013 to 2017. All firms for which a match in Orbis was found are included. Emissions in percentage; free allocations in millions

Table A.2: Estimated compensations for carbon leakage in million EUAs

Free Allowances				
Year	Current	Reduced	Difference	Market Value
2013	663			
2014	643	594	49	290
2015	626	515	112	856
2016	620	449	171	972
2017	598	398	201	1171

Notes: Estimated compensations for carbon leakage in million EUAs. The estimates are obtained by comparing the current free allowances obtained by firms protected from carbon leakage and applying the same reduction factor of the non protected firms. The market value is calculated multiplying the estimated difference by the spot price of EUAs and is expressed in M€.

B. Model derivations

B.1 Cost minimizing choice of energy sources and the firm's emission choice

We begin by considering the firm's choice of individual energy sources that minimizes total energy costs. To produce the aggregate energy input E the firm solves the following problem:

(B.1) $$\min_{e_1,\dots,e_S} \sum_{s=1}^{S}(p_s^e + \tau c_s)e_s \qquad \text{s.t.} \quad \left(\sum_{s=1}^{S}\eta_s e_s^{\theta}\right)^{\frac{1}{\theta}} \geq E$$

Exponentiating both sides of the constraint in (B.1) to the power of θ without loss of generality, we form the Lagrangean:

(B.2) $$\mathcal{L} = \sum_{s=1}^{S}(p_s^e + \tau c_s)e_s + \lambda\left(E^{\theta} - \sum_{s=1}^{S}\eta_s e_s^{\theta}\right)$$

The first order condition with respect to e_s for each $s = 1,\dots, S$ is:

(B.3) $$p_s^e + \tau c_s = \lambda\theta\eta_s e_s^{\theta-1}$$

Let $\tilde{p}_s = \frac{p_s^e + \tau c_s}{\eta_s}$ and solve (B.3) for e_s:

(B.4) $$e_s = \left(\frac{\tilde{p}_s}{\lambda\theta}\right)^{\frac{1}{\theta-1}}$$

Substitute (B.4) in the constraint of problem (B.1) to get:

(B.5) $$E = \left[\frac{\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}}{(\lambda\theta)^{\frac{\theta}{\theta-1}}}\right]^{\frac{1}{\theta}}$$

Substituting the S first order conditions (B.3) into the objective function of problem (B.1) and using the definition of $\tilde{p}_s$ yields the cost function:

(B.6) $$C(\lambda) = \frac{\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}}{(\lambda\theta)^{\frac{1}{\theta-1}}}$$

To eliminate the Lagrange multiplier λ we solve (B.5) for $(\lambda\theta)^{\frac{1}{\theta-1}} = \frac{1}{E}\left(\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}\right)^{\theta}$ and use it into (B.6) to get a cost function that depends on the amount of total energy E used in production:

(B.7) $$\tilde{C}(p_s^e, \tau, E; \eta, \theta) = E\left(\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}\right)^{\frac{\theta-1}{\theta}}$$

The unit cost of energy $\tilde{C}$ depends on the price vector of energy sources p^e, the carbon price τ, and the vector η collecting the parameters η_s and θ. By Shephard's lemma we obtain from (B.7) the conditional demand function for each energy source e_s:

(B.8) $$e_s = E\frac{\tilde{p}_s^{\frac{1}{\theta-1}}}{\left(\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}\right)^{\frac{1}{\theta}}}$$

Total carbon emissions CE are given by the sum of emissions produced from the different energy sources, according to their carbon content. Using (B.8):

(B.9) $$CE = \sum_{s=1}^{S} c_s e_s = E\frac{\sum_{s=1}^{S} c_s \tilde{p}_s^{\frac{1}{\theta-1}}}{\left(\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}\right)^{\frac{1}{\theta}}}$$

Finally, using (B.9) we can express the energy cost function (B.7) in terms of emissions:

(B.10) $$C(p_s^e, \tau, CE; \eta, \theta) = CE \cdot P(p^e, \tau; \eta, \theta) = CE \cdot \left[\left(\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}} \right) \left(\sum_{s=1}^{S} c_s \tilde{p}_s^{\frac{1}{\theta-1}} \right)^{-1} \right]$$

Expression $P(p_s^e, \tau; \eta, \theta)$ is the per-emission cost sustained by the firm to produce one additional unit of energy. Equations (B.9) and (B.10) allow us to write the firm's profit maximization problem in terms of emission choices rather than energy source choices.

B.2 Comparative statics of emission intensity

We now compute the effect of a change in the price of individual energy sources on emission intensity *e*. From equations (7) and (11) in the main text we have:

(B.11) $$e = \frac{\alpha}{P(p^e, \tau; \eta, \theta)} = \alpha \left(\frac{\sum_{s=1}^{S} c_s \tilde{p}_s^{\frac{1}{\theta-1}}}{\sum_{s=1}^{S} \eta_s \tilde{p}_s^{\frac{\theta}{\theta-1}}} \right)$$

We now differentiate *e* with respect to p_s^e, that is:

(B.12) $$\frac{\partial e}{\partial p_s^e} = \frac{\partial e}{\partial \tilde{p}_s} \frac{\partial \tilde{p}_s}{\partial p_s^e} = \frac{1}{\eta_s} \frac{\partial \tilde{p}_s}{\partial p_s^e}$$

$$= \frac{\alpha}{\eta_s} \left[c_s \frac{1}{\theta - 1} \tilde{p}_s^{\frac{2-\theta}{\theta-1}} \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right) - \sum_{s'} \frac{\theta}{\theta - 1} \left(\sum_{s'} c_{s'} \tilde{p}_{s'}^{\frac{1}{\theta-1}} \right) \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right)^{-2} \tilde{p}_s^{\frac{1}{\theta-1}} \eta_s \right]$$

$$= \frac{\alpha}{\eta_s(\theta - 1)} \tilde{p}_s^{\frac{2-\theta}{\theta-1}} \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right)^{-2} \left[\left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right) c_s - \theta \left(\sum_{s'} c_{s'} \tilde{p}_{s'}^{\frac{1}{\theta-1}} \right) \tilde{p}_s \eta_s \right]$$

$$= \frac{\alpha}{\eta_s(\theta - 1)} \tilde{p}_s^{\frac{2-\theta}{\theta-1}} \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right)^{-2} \left[\sum_{s' \neq s} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} (c_s \eta_{s'} \tilde{p}_{s'} - \theta c_{s'} \tilde{p}_s \eta_s) \right]$$

$$= \frac{\alpha}{\eta_s(\theta - 1)} \tilde{p}_s^{\frac{2-\theta}{\theta-1}} \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right)^{-2} \left\{ \sum_{s' \neq s} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} [c_s(p_{s'}^e + \tau c_{s'}) - \theta c_{s'}(p_s^e + \tau c_s)] \right\}$$

$$= \frac{\alpha c_s}{\eta_s(\theta - 1)} \tilde{p}_s^{\frac{2-\theta}{\theta-1}} \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right)^{-2} \left\{ \sum_{s' \neq s} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} c_{s'} \left[\frac{\theta(p_s^e + \tau c_s)}{c_s} - \frac{p_{s'}^e + \tau c_{s'}}{c_{s'}} \right] \right\}$$

$$= \frac{\alpha \theta c_s}{\eta_s(\theta - 1)} \tilde{p}_s^{\frac{2-\theta}{\theta-1}} \left(\sum_{s'} \eta_{s'} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \right)^{-2} \left[\left(\frac{p_s^e + \tau c_s}{c_s} \right) - \frac{1}{\theta} \sum_{s' \neq s} \tilde{p}_{s'}^{\frac{\theta}{\theta-1}} \omega_{s'} \left(\frac{p_{s'}^e + \tau c_{s'}}{c_{s'}} \right) \right]$$

where: $\omega_{s'} = \left(\frac{p_{s'}^e + \tau c_{s'}}{c_{s'}} \right)^{\frac{1}{\theta-1}} \left[\sum_{s'' \neq s} \left(\frac{p_{s''}^e + \tau c_{s''}}{\eta_{s''}} \right)^{\frac{1}{\theta-1}} \right]^{-1}$ and $\sum_{s' \neq s} \omega_{s'} = 1$. If $\theta < 1$ then:

(B.13) $$\frac{\partial e}{\partial p_s^e} \geq 0 \quad \Leftrightarrow \quad \frac{p_s^e}{c_s} + \tau \geq \frac{1}{\theta} \sum_{s' \neq s} \left(\frac{p_{s'}^e}{c_{s'}} + \tau \right)$$

The emission intensity e increases with an increase in price of the energy source p_s^e if the price is relatively low or its carbon content c_s is relatively high, when compared to the other energy sources. For example, for $\theta = 1$ – the limiting case of perfectly substitutable energy source – the condition can be expressed by the following weighted average: $\frac{p_s^e}{c_s} \geq \sum_{s' \neq s} \left(\frac{p_{s'}^e}{c_{s'}} \right)$, which motivates the argument in Section 3.2 of the main text.

C. Unobserved emission intensities and free allowances

Consider firms that invest exclusively outside or inside the regulated area in a given year. The emission intensity of the former (3.7 tons per thousand euros sales) is on average 60% higher than the latter (1.9 tons per thousand euros sales). Within- industry comparisons provide the same result, as firms that invest outside of the EU ETS are on average more emission intensive in 26 out of 33 industries. This difference is in line with the theoretical model, which suggests that emission intensive firms have, everything else equal, a higher incentive to invest outside of regulated countries. This effect could be offset by free allowances, which aim at keeping investments within the EU ETS area. Indeed, firms that invest outside of the EU ETS also receive more free allowances to cover the emissions they produce domestically. On average, they receive 2.6 free allowances per thousand euros sales, while the firms that invest within the EU ETS receive 1.7 free allowances per thousand euros sales. As a statistical test, we use a logit regression where we consider the firms investing only outside of the EU ETS regulated area in a given year against the firms investing only inside of it. Table C.1 reports the results.

Table C.1: Test of difference between firms investing outside of the EU ETS from those investing inside

	coefficient	Standard error
Emissions per sales e_{i0t}	0.055	(0.028)
Free allowances per sales e_{i0t}^*	-0.051	(0.030)
Constant	-0.652	(0.117)
Observations	335	

Both coefficients are statistically significant at a 90% confidence level (p-values: 0.051 and 0.090 respectively). This means that firms that invest outside of the EU ETS emit more and receive less free allowances, after controlling for their emitting level. The signs of this correlation do not change when conditioned on the country of origin, the year or a measure of the firm size. Moreover, the difference between the two groups in e_{ijt} remains always significant at a 90% confidence interval.

D. Missing data on energy prices

Energy prices data presents some missing values, especially concentrated in the price of coal. To address the problem, we estimate the following models:

$$p_{sjt}^{e} = \rho_{sj}^{0} + \rho_{sj}^{1} p_{sjt-1}^{e} + W_{sjt}' \rho_{s}^{2} + d_{st} + u_{sjt} \quad \text{(D.1)}$$

where p_{sjt}^{e} are the energy prices of the four energy sources considered (oil, gas, electricity, coal) in country j and year t, d_{st} are year fixed effects and u_{sjt} is an iid error. The vector W_{sjt} contains observable variables that can help predict the price of energy sources: the price of the same source available for energy producers or household consumers; the price of a similar source in the same category in the country (e.g. low sulfur oil prices for fuel oil); an industrial price index for the same source (provided by the IEA); the commodity price in the closest international market (e.g. Brent or WTI oil prices, Australian coal price); the IEA import price in Europe for coal net of insurance and freight costs. In addition, for coal we use data from neighboring countries for Czech Republic, Denmark, Netherlands, Spain, Sweden and Norway. The predicted values from model (C.1) are used to impute the missing data described in Section 4.

E. Model selection and cross validation

The model has been selected through k-class cross validation (k = 301). Cross validation aims at reducing the risk of overfitting non-parametric models trading off bias and variance of the non-parametric estimation. Let z be a "hyper-parameter" vector describing fully the competing models. As we restrict here attention to second-order polynomial approximations, z is a vector of length 20 that contains 0's and 1's which determining what covariates from the polynomial $p(z)$ are fit to the data. That is:

$$p(z) = \left[\tau_{jt}^{z_1}, \left(p_{oiljt}^{e_1}\right)^{z_2}, \dots, \left(\tau_{jt}^{2}\right)^{z_6}, \dots, \left(\tau_{jt} \cdot p_{oiljt}^{e}\right)^{z_{11}}, \dots, \left(p_{gasjt}^{e} \cdot p_{coaljt}^{e}\right)^{z_{20}}\right] \quad \text{(E.1)}$$

so that when, for example, z = {1,1,1,1,1,0,...,0}, only the linear prices are used as independent variables.

We select the model that minimizes the following means squared error, operating a supervised search over possible values of z:

$$MSE(z) = \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} [\hat{y}_{it}(z) - y_{it}]^2 \quad \text{(E.2)}$$

where $\hat{y}_{it}(z)$ is the value of y predicted by the model with hyper-parameter z. The mean squared error is the sum of two components: an estimation of the bias $E[\hat{y}_{it}(z)] - y_{it}$, which is decreasing with the order of polynomial approximation, and a variance term, $E\{\hat{y}_{it}(z) - E[\hat{y}_{it}(z)]\}^2$ increasing with it. Minimizing this objective represents a good trade-off between the two.

We obtain estimates of $\widehat{MSE}(z)$ using k-class cross validation. For each competing model z the algorithm works as follows: (1) the sample is divided into k "validation classes" composed of the same number of firms; (2) the first validation class is taken out and the model is estimated on the remaining classes; (3) the $\widehat{MSE}_1(z)$ is estimated; (4) the process is repeated for all k classes. Taking averages across the classes we obtain the estimate $\widehat{MSE}(z) = \frac{1}{k}\sum_k \widehat{MSE}_k(z)$.

The method is bound by computational times. In view of this we first limit attention to 301 classes, instead of resorting to leave-one-out cross validation (leave-one-out cross validation – LOOCV - is a specialization of k-class cross validation with k = N, which is more thorough but also more computationally intensive), where 301 has been chosen to be reasonably big while being a (near) round divisor of sample size. Second, it is impossible to check all the 2^{20} combinations for a second order polynomial. Thus, we consider only models containing all linear parameters inside as we have a direct interest in them. Then we proceed by addition, nesting each model in the previous one. This precaution excludes, for example, models with only interactions but not squared terms. Instead of 1,048,576, we compare (only) 13 models. Finally, the cross validation has been performed on two models: the "basic" one with only firm fixed effects and the one with industry-specific elasticities and firm fixed effects. In the end we base the final decision on the results obtained for the former for two reasons. First and foremost, because of some of the failed sub-sampling attempts in the case with industry-specific elasticities, due to the presence of relatively few observations for some industries. Second, because we use the former specification as a base for the following analysis, we consider it the predominant one. The next table E.1 presents the estimates for the $MSE(z)$ for the 13 models considered. The model finally selected (model 10 in the table) contains: the linear prices, their square, the interaction of carbon price with all the other energy prices, and the interaction of oil prices with electricity and gas prices.

Table E.1: Cross validated mean squared errors

k	$MSE(z)$
1	14612.91
2	14613.37
3	14562.17

4	14543.81
5	14544.22
6	14461.89
7	14423.01
8	14423.53
9	14420.42
10	14419.88
11	14420.94
12	14421.44
13	14421.40

F. Calculation of expected compliance costs

Section 5.3 in the main text describes how emissions were estimated: see equation (12). To measure the precision of the estimates we employ a bootstrap procedure. Using asymptotic theory to construct tests is in principle feasible, since we have the estimated variance-covariance matrix of the coefficients from (10), but it is not advisable. Since the fixed effects are identified only by within variations and the panel is short, the bootstrap is better suited for small sample testing. We thus randomly resample the data in "blocks" in which each firm *i* has equal probability of being chosen. Resampled data are constituted of the selected *is* and all its associated observations. We then estimate $\hat{e}_{ijt}(r)$ using equation (12) where *r* indexes one of 200 repetitions. From the distribution of estimated values, we can construct bootstrapped confidence intervals by taking the corresponding percentiles. We use the 5th and 95th percentile, $\hat{p}(5)_{ijt}$ and $\hat{p}(95)_{ijt}$, to obtain a 90% confidence interval. Letting N_r be the number of repetitions the firm appears in, the standard deviation of $\hat{E}_{ijt}(r)$ can be estimated using the expression $\hat{s}_{ijt} = \left\{(N_r - 1)^{-1} \sum_r \left[\hat{E}_{ijt}(r) - \hat{E}_{ijt}\right]^2\right\}^{1/2}$. To be able to compare different firms, we consider a normalized confidence interval NCI_{ijt} in the following way:

$$NCI_{ijt} = \left[\frac{\hat{e}_{ijt} - \hat{p}(5)_{ijt}}{\hat{s}_{ijt}}, \frac{\hat{p}(95)_{ijt} - \hat{e}_{ijt}}{\hat{s}_{ijt}}\right] \quad \text{(F.1)}$$

It is worth noting that 58.1% of the estimated emissions are significantly different from zero, i.e. $0 \notin NCI_{ijt}$. Across the sample, the average lower bound of the confidence interval is equal to 0.93 standard deviations and the average upper bound of the confidence interval is equal to 0.157 standard deviations (three firms active in the transport sector have been excluded from this and subsequent analysis because their bounds were unreasonably large). This means that the model is more imprecise when predicting positive deviations from the mean rather than negative.

Using estimated net emissions, we compute expected compliance costs per unit of revenue $ETS_{ijt} = \tau_{jt}(e_{ijt} - e^{*}_{ijt})$. Variation in ETS_{ijt} drives identification of the effect of carbon pricing on investments. Since it is a constructed variable, it is important to know where this variation comes from. We therefore present an analysis of variance (ANOVA) in Table F.1 along three dimensions: the country where the investment is directed *j*, the year *t*, and the industry *k*. The first two dimensions capture the effect of local energy and allowance price on the cost for emissions, while the third one captures all between-industry difference. The part of the ETS_{ijt} that is left unexplained is due to variations in α_i which are not explained by industry differences.

Table F.1: Analysis of variance of ETS_{ijt}

Source	*SS*	*df*	*MS*	*F*	*p-value*	*SS/SSTOT*
Model	6115	7217	0.847	13.58	0.000	9.8 %
j	130	41	3.164	50.72	0.000	0.2 %
k	212	22	9.627	154.32	0.000	0.3 %
t	10	7	1.362	21.84	0.000	0.0 %
$j \, x \, k$	1 328	887	1.497	24	0.000	2.1 %
$j \, x \, t$	54	287	0.189	3.03	0.000	0.1 %
$t \times k$	115	145	0.792	12.69	0.000	0.2 %
$j \, x \, k \, x \, t$	1212	5828	0.208	3.33	0.000	1.9 %
Residual	56511	905868	0.062			90.2 %
Total	62626	913085	0.069			100.0 %

Notes: The table reports the sum of squares (*SS*), the degrees of freedom (*df*), the mean squares (*MS*), F-ratios (*F*), p-values and the ratio of the sum of squares for that variable divided by the total sum of squares (*SS/SS_{TOT}*). This last element is the percentage of variance in ETS_{ijt} due to the explanatory variables listed in the first column.

Even after taking into account differences between industries, more than 90% of the variation is due to between-firm differences. This fact makes evident that the results of the estimated location decision model of section 5.4 are mostly driven by idiosyncratic differences between firms which cannot be explained by resorting to industry comparisons alone.

FONDAZIONE ENI ENRICO MATTEI WORKING PAPER SERIES

"NOTE DI LAVORO"

Our Working Papers are available on the Internet at the following address:
https://www.feem.it/pubblicazioni/feem-working-papers/

"NOTE DI LAVORO" PUBLISHED IN 2022

1. 2022, Daniele Crotti, Elena Maggi, Evangelia Pantelaki, Urban cycling tourism. How can bikes and public transport ride together for sustainability?
2. 2022, Antonio Acconcia, Sergio Beraldo, Carlo Capuano, Marco Stimolo, Public subsidies and cooperation in research and development. Evidence from the lab
3. 2022, Jia Meng, ZhongXiang Zhang, Corporate Environmental Information Disclosure and Investor Response: Empirical Evidence from China's Capital Market
4. 2022, Mariagrazia D'Angeli, Giovanni Marin, Elena Paglialunga, Climate Change, Armed Conflicts and Resilience
5. 2022, Davide Antonioli, Claudia Ghisetti, Massimiliano Mazzanti, Francesco Nicolli, The economic returns of circular economy practices
6. 2022, Massimiliano Mazzanti, Francesco Nicolli, Stefano Pareglio, Marco Quatrosi, Adoption of Eco and Circular Economy-Innovation in Italy: exploring different firm profiles
7. 2022, Davide Antonioli, Claudia Ghisetti, Stefano Pareglio, Marco Quatrosi, Innovation, Circular economy practices and organisational settings: empirical evidence from Italy
8. 2022, Ilenia Romani, Marzio Galeotti, Alessandro Lanza, Besides promising economic growth, will the Italian NRRP also produce fewer emissions?
9. 2022, Emanuele Ciola, Enrico Turco, Andrea Gurgone, Davide Bazzana, Sergio Vergalli, Francesco Menoncin, Charging the macroeconomy with an energy sector: an agent-based model
10. 2022, Emanuele Millemaci, Alessandra Patti, Nemo propheta in Patria: Empirical Evidence from Italy
11. 2022, Daniele Valenti, Andrea Bastianin, Matteo Manera, A weekly structural VAR model of the US crude oil market
12. 2022, Banchongsan Charoensook, On Efficiency and Stability in Two-way Flow Network with Small Decay: A note
13. 2022, Shu Guo, ZhongXiang Zhang, Green credit policy and total factor productivity: Evidence from Chinese listed companies
14. 2022, Filippo Bontadini, Francesco Vona, Anatomy of Green Specialisation: Evidence from EU Production Data, 1995-2015
15. 2022, Mattia Guerini, Fabio Vanni, Mauro Napoletano, *E pluribus, quaedam*. Gross domestic product out of a dashboard of indicators
16. 2022, Cinzia Bonaldo, Fulvio Fontini, Michele Moretto, The Energy Transition and the Value of Capacity Remuneration Mechanisms
17. 2022, Giovanni Marin, Francesco Vona, Finance and the Reallocation of Scientific, Engineering and Mathematical Talent
18. 2022, Anna Laura Baraldi, Erasmo Papagni, Marco Stimolo, Neutralizing the Tentacles of Organized Crime. Assessment of Anti-Crime Measure in Fighting Mafia Violence
19. 2022, Alexander Golub, Jon Anda, Anil Markandya, Michael Brody, Aldin Celovic, Angele Kedaitiene, Climate alpha and the global capital market
20. 2022, Jlenia Di Noia, Agent-Based Models for Climate Change Adaptation in Coastal Zones. A Review
21. 2022, Alberto Gabino Martínez-Hernández, System Dynamics modelling and Climate Change Adaptation in Coastal Areas: A literature review
22. 2022, Pietro De Ponti, Matteo Romagnoli, Financial Implications of the EU Emission Trading System: an analysis of wavelet coherence and volatility spillovers
23. 2022, Laura Cavalli, Mia Alibegovic, Davide Vaccari, Andrea Spasiano, Fernando Nardi, Sustainability assessment of the public interventions supported by the ReSTART project in the CITI4GREEN framework
24. 2022, Filippo Maria D'Arcangelo, Giulia Pavan, Sara Calligaris, The Impact of the European Carbon Market on Firm Productivity: Evidence from Italian Manufacturing Firms.
25. 2022, Enrico Turco, Davide Bazzana, Massimiliano Rizzati, Emanuele Ciola, Sergio Vergalli, Energy prices shocks and macroeconomic stabilization policies in the MATRIX model
26. 2022, Mario Gilli, Filippo Giorgini, Citizens Protests: causes and consequences. A Research on Regime Change and Revolutionary Entrepreneurs

“NOTE DI LAVORO” PUBLISHED IN 2022

27. 2022, Filippo Maria D'Arcangelo, Marzio Galeotti, Environmental Policy and Investment Location: The Risk of Carbon Leakage in the EU ETS

Fondazione Eni Enrico Mattei
Corso Magenta 63, Milano – Italia

Tel. +39 02 403 36934

E-mail: letter@feem.it
www.feem.it

Fondazione Eni Enrico Mattei