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Carbon Taxation, Investment and Leakage

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Carbon Taxation, Investment and Leakage*†

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Abstract

This project studies the implications of carbon taxation on the firm's investment decision in clean technology and how this can direct aggregate technical change. A higher carbon tax encourages more green investments and gives rise to a cleaner aggregate economy. However, it could also lead to increased competition from imported goods and even encourage the relocation of polluting firms to regions with weaker environmental regulations. Leveraging data from the EU Emissions Trading System (ETS) spanning the period 2005 to 2018, I construct a novel investment indicator that reveals the role of price expectations in investment decisions. Notably, more productive, and polluting firms tend to invest more in clean technology when they anticipate a high carbon price. To quantitatively examine the aggregate impact of this taxation and the subsequent investment decisions, I propose a model of heterogeneous firms that incorporates these firm characteristics and explores how governments can direct technical change. The model demonstrates that the EU ETS is an effective tool for reducing climate emissions, However, while firms transition towards greener practices, the largest firms are better positioned to capitalize on policy, leading to their further expansion and exacerbating inequalities across firms. This paper sheds light on the dynamics of firm decision-making processes in the context of the EU ETS, providing insights into the significant, yet heterogeneous, implications of policies that aim to combat climate change.

*__Confidential Notice: This document is not intended for further distribution. It represents preliminary work, and the results contained herein are subject to change.__

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1. Introduction

In the global effort to reduce emissions, governments across the world have introduced carbon taxes and cap-and-trade schemes. These measures, from voluntary initiatives like the Africa Carbon Markets Initiative to more stringent actions in Nordic countries, reflect a collective commitment to combat climate change. However, the potential adverse effects of taxing carbon emissions on aggregate economic activity are a central point of discussion among academics and policy-makers (Dolphin et al., 2020).[1]

The rationale of the implementation of this policy is to lays the decision at the level of the industry and firms themselves to be able to decide themselves whether to invest in clean technology. The outcomes of this approach are evident, particularly in the European Union, where the aggregate emission intensity (total emissions over total value added) has been decreasing. While policymakers highlight this reduction as a testament to the success of their policies, critics point towards carbon leakage, involving the relocation of emission-intensive processes to regions with less stringent emission taxation schemes, as the primary driver, argue that the policy might affect firms that do not have the capacity adopt cleaner practices. Figure 1 documents a clear decrease in aggregate emission output per value added in the right panel for all firms operating under the European Emission Transaction System (EU ETS), but it also shows that this is associated with a decreasing dispersion in emission intensity and a rising variation in value added, which suggests that, indeed, the implications of this policy are granular.

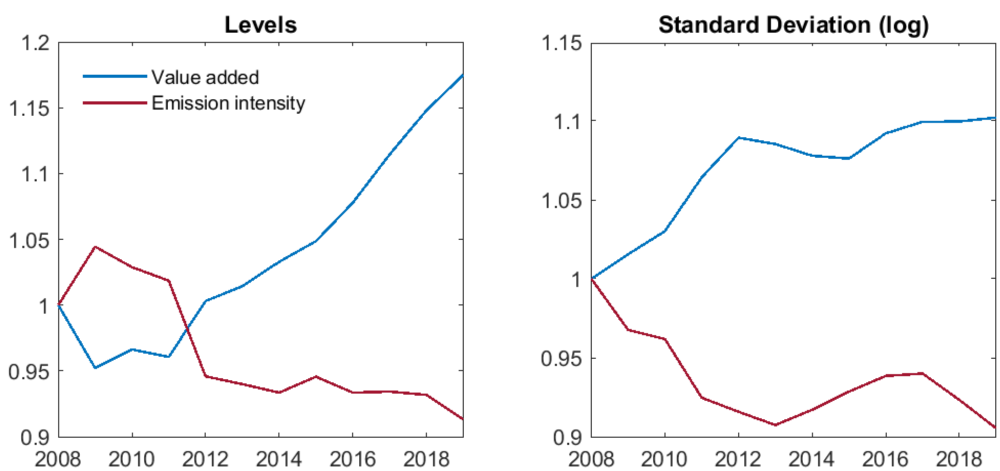

Figure 1: Aggregate Evolution of firms in EU ETS

The left panel depicts a graphical overview of the changes in total value added and emission intensity (emissions over value added) of firms since 2008, utilizing a 2-year moving average. The right panel illustrates the progression of inequality, measured by the standard deviation of the logarithm of both value added and emission intensity using a 2-year moving average as well.

This study aims to analyze the mechanism behind the reduction in emission output and how governments can achieve technical change. I begin by examining the mechanisms by which firms decide to invest

[1] For instance, since these efforts are not yet globally coordinated, they allow for the threat of firms to relocate to locations with less stringent emission taxation schemes.

in clean technology when faced with the EU ETS, the most elaborate emission reduction policy to date. Leveraging extensive firm-level data encompassing emission intensity across all countries participating in the policy scheme, a new indicator is developed to signify whether a firm has undergone a substantial and structural reduction in emission intensity. This indicator is then employed to investigate the characteristics of firms that have achieved significant emission reductions and whether this is because of the price of the carbon certificates.

Building upon these insights, a model is proposed that incorporates these mechanisms and explore how governments can direct their carbon policies to speed up investment. The model is calibrated to the transition of the EU firms from the start of the policy and looks at the transition to now. The firms in the model are forward looking and also face import competition from a non-regulated 'foreign' country. The model's flexibility allows for a nuanced yet comprehensive analysis of changes in aggregate emission intensity in the EU. Unlike traditional program evaluation methods, this model is adept at capturing general equilibrium forces through trade and competition while also able to account for the forward-looking behavior of firms.

The results indicate that firms that invest in clean technology are on average larger and pollute more prior to their investment relative to those that will not invest. I then show that the price of carbon bites more for these firms as the investments occur more often for emission-intense firms and that emission intense multinational firms are more likely to relocate away from the European market when the price is high, hinting at carbon leakage. The shift towards clean technology is primarily driven by investment rather than innovation, inducing a catch-up mechanism where polluting firms will become more green over time. The structural model illustrates that while firms are on average becoming greener (i.e. the distribution of clean technology converges), the largest firms can best capitalize on the carbon policy and will become even larger, which exacerbates the inequality in value added across firms (or any other measure of size). a breakdown of aggregate emission reduction reveals that the sensitivity of the investment decision is highly affected by trade channel. Lastly, I examine various counterfactual scenarios among which the Carbon Border Adjustment Mechanism (CBAM) and the progress toward the goals outlined in the Paris Agreement.

This paper contributes to the existing literature in three key aspects. Firstly, it explicitly models the investment decisions of firms when confronted with carbon policies building upon the literature concerning emission abatement within structural modelling (Copeland and Taylor, 2004; Shapiro and Walker, 2018; Forslid et al., 2018). I argue that the emission abatement is mainly through sunk investments. In particular, it builds upon Forslid et al. (2018) who already document that large more productive firms will invest more in clean technology.[2] This paper extends this literature by demonstrating that the future level of clean technology does not only depend on the firms size, but also on the current level of clean technology.

Second, this paper explores an open economy and highlights how the trade channel impacts the investment decision. This ties in on the literature of carbon leakage (FontagnÃ© and Schubert, 2023) that

[2]In a survey based on Swedish manufacturing firms, Forslid et al. (2018) discuss that most of the of the cost aimed at reducing emissions are related to new machinery and equipment which are costly and very invariable.

analyzes open economies and their responses to carbon leakage and subsequent policies mitigating it, such as the CBAM. Additionally, there is a small empirical literature on the effect of carbon leakage on firms active in the EU ETS (Verde, 2020) but the answer on this question is mixed for the direct effects of trade. Borghesi et al. (2020) shows that the EU ETS has incited some form of carbon leakage for large multinational firms through the increased number of affiliates outside the EU and DechezleprÃªtre et al. (2019) argue that modest leakage might have happened within multinationals that are active in- and outside the EU.[3]

The third and final contribution lies in providing additional evidence on the implications of the EU ETS on the competitive landscape of firms and its effects on firm dynamism. Existing literature has predominantly focused on the short-term implications of the policy's impact on the competitive position of firms, often relying on quasi-experimental research designs (DechezleprÃªtre and Sato (2017), Martin et al. (2014), among others, see Verde (2020) for a comprehensive overview). They find that firms are able to pass their prices through to the consumers, and increase investment. This paper goes beyond by demonstrating that the carbon policy not only affects the competitive position of directly impacted firms but also has broader economic implications, even for those less affected. The ongoing wave of green technical change is emphasized (Calel and DechezleprÃªtre, 2016), with larger firms positioned to better absorb substantial sunk costs associated with the adoption of new clean technology. Consequently, large firms, who are best suited to pay these costs, are thus become greener and reduce their expenses on this taxation. This trend, however, leaves smaller firms behind, who either leave or are too constrained, creating space for larger firms to further expand and contributing to an increase in overall inequality. This study offers an additional explanation for the growing inequality observed in the manufacturing sector (Autor et al., 2020).

This paper is structured as follows. Section 2 describes the institutional setting of the EU ETS system and describes how the policy shapes the investment decisions for firms. Section 3 presents the associated dataset used in this analysis and describes the creation of the new indicator of investment. Additionally, it explores which firms invest in clean technology and how this decision depends on the price of carbon emissions. Section 4 characterizes the structural model of firm dynamics to quantitatively asses the aggregate effects of the carbon emission policy. Section 5 calibrates the model on the European setting and examines the heterogeneous implications of the policy. Section 6 conducts robustness tests and explores diverse counterfactual scenarios.[4] Finally, Section 7 concludes.

[3]The empirical section of this paper finds that multinational exit is also associated with a higher share of freely allocated certificates. But this analysis, akin to many papers examining the effect of the EU ETS on carbon leakage, suffers from the fact, as pointed out by FontagnÃ© and Schubert (2023), that the carbon price has been too low to find any substantial effects.

[4]Section 6 is currently under construction and has not been completed in time

2. Institutional setting

2.1 The EU Emission Transaction System

The European Union has set up one of the world's largest cap-and-trade systems for regulating greenhouse gas emissions. The EU ETS, or the European Union Emissions Trading System, is a key policy tool used by the EU to address climate change and reduce carbon emissions. The following paragraphs provide a short overview of the trading system. An extensive summary on the EU ETS can be found at the website of the European union on climate action.[5,6]

The EU ETS sets a limit (cap) on the total (industry) emissions that can be omitted each year. It does not decide for any measure for firms to become cleaner, but encourages firms themselves to find cost-effective ways to reduce emissions through the adoption of cleaner technologies, energy efficiency measures, and other strategies to mitigate climate change. This way, the governmental body leaves it to the individual firm to find the most effective way to become less polluting.

To address concerns about the competitiveness and economic impact of carbon pricing and prevent potential negative economic impacts, firms are allocated free emissions allowances. The aim is to disincentives firms from relocating their polluting production to regions with less environmental regulation. This threat is taken extremely seriously by the national governments.[7] The allocation of free certificates is based on the ex-ante profile of the firm, in order not to disincentive firms that want to invest. If the firms omit more (less) emissions that those they are relocated beforehand, they have to buy (sell) additional certificates form a liquid secondary market given the available spot price. In cooperation with the industry, the EU has declared that the number of freely allocated certificates would reduce slowly at an ex-ante determined rate to approximatly 80% in 2020.

The policy has progressed through four distinct phases: Phase 1 (2005-2007) marked its inception, but it faced challenges due to over-allocation of allowances, resulting in incomplete markets with low carbon prices. It has often been described as a phase of learning, both for the governmental agency as for the participating firms. Later, phase 2 (2008-2012) was the first true carbon reduction phase. It saw the expansions of the market and reductions in free allowances, and it was accompanied by an increase in price of the Carbon emissions and a fully grown secondary emission market where agents could trade without the participation of the government. The cap on the total emissions was further tightened in phase 3 (2013-2020) and the supply of free allocated emission allowances reduced. Phase 4 (2021-2030) is geared towards achieving more ambitious emission reduction targets. Each phase has aimed to refine the system and strengthen its

[5] EU Emissions Trading System (EU ETS)

[6] The Cap-and-trade system differs from a carbon taxation in several ways. Carbon taxation imposes a tax on emissions directly, providing cost predictability but at a cost of flexibility (Metcalf, 2023). However, within the structure of the structural model used throughout the text, these two systems coincide as the frontier of the technological progress is equal for all firms and we abstract from business cycle fluctuations. Section 4 provides a full overview of the model.

[7] For many countries, the allocation of free emissions allowances was a necessary step to approve the agreement. Additionally, some countries such as Belgium, The Netherlands and France even have additional subsidies in place to make it even more improbable that firms decide to move abroad.

role in mitigating climate change.

2.2 Climate policy

To illustrate the conceptual trade-offs that forward-looking firms will have to make when faced with the EU Emission policy, I introduce the following simplified dynamic model. This framework also presents notation that will be used throughout the paper.

The government has at its disposal two policy instruments that it can utilize to encourage firms to invest in clean technology while mitigating the risk of them relocating abroad. First, it can increase the price of the carbon taxation ζ - or the spot price of the carbon certificates by limiting the supply of the certificates. Second, to discourage firms from relocating to pollution havens, the government can offer firms a number of free certificates to firms based on the initial conditions of the firm. As the allocation of free certificates is known beforehand, it can be seen as a fixed cost subsidy κ.

Given these governmental policies, firms face three alternatives. They can either choose to comply by the policy, which gives them the option to do nothing, or to invest and reduce the impact on their marginal cost, or thirdly, they can opt to cease compliance and relocate abroad where such policies are absent, a phenomenon referred to as carbon leakage. The firms are heterogeneous in their level of clean technology s which encompasses both the input composition and the capacity of the firm to omit less.[8] A higher level of $s \in \mathbb{R}_0^+$ is cleaner and makes the firm thus less prone to the taxation. Firms maximize their present value $v(s) = \pi(s) + \beta \mathbb{E}_{\zeta,\kappa}[v(s')]$, and base their decisions on the expected future policies (ζ,κ) with static profits π_t and discount factor $\beta \in (0,1)$.

To decrease the total emission output of the industry, the government can establish a taxation rate ($\zeta > 0$) on the level of clean technology such that every firm will be required to pay a variable cost of for each good produced. The value v is characterized by $\partial v(s;\zeta,\kappa)/\partial s > 0$, and $\partial^2 v(s;\zeta,\kappa)/\partial^2 s < 0$. Every period, firms have the option to invest ($\omega = 1$) and adopt a new level of clean technology at a cost k_ω which increases their level of clean technology ($s' = s + \chi$) where the cost k_ω is normalized relative to not investing. The investment decision is based on the governmental policies κ and ζ.

$$\Delta v(s;\kappa,\zeta) \equiv v'(s+\chi;\kappa,\zeta) - v'(s;\kappa,\zeta) > k_\omega \tag{1}$$

Firms will only invest in clean technology if the marginal increase in profits Δv out-weights the cost of the investment k_ω. Note that if the taxation $\zeta = 0$, then $v(s;\kappa,\zeta = 0) = v$ for all s. Hence, they do not internalize other indirect effects in their investment decision - i.e. negative externalities, either through lower consumer value or increased aggregate risks - and will only invest if they are forced to do so.

In order to avoid being subjected to the carbon taxation, companies may choose to relocate their operations overseas ($\xi = 1$), incurring a relocation cost denoted as k_ξ. By operating abroad, firms become exempt

[8] I adhere to the main objective of the EU ETS, whereby firms are entrusted with the autonomy to determine the most effective measures for reducing their emission output.

from the taxes ζ and κ, and thus their future profits are not impacted by their level of clean technology.

$$\Delta v^f \equiv v'^f(s;\kappa,\zeta) - v'(s;\kappa,\zeta) > k_\xi \tag{2}$$

Here v' denotes the future value for the firm exposed to the taxation at home and v^f the constant value abroad (foreign). Throughout the text, parameters concerning the foreign country will be indexed with f.

Hence, firms face a trade-off where they will choose to move abroad if their value from moving abroad minus the cost of moving abroad is higher than their future value of investing minus the cost of investing. This way, the set of firms that invest and move abroad is empty.

$$\Delta v^f(s,\kappa,\zeta) - k_\xi > \Delta v(s,\kappa,\zeta) - k_\omega \tag{3}$$

Additionally, firms can decide to do nothing at all if the cost of either clean technology adoption or moving abroad is higher than their expected gained value.

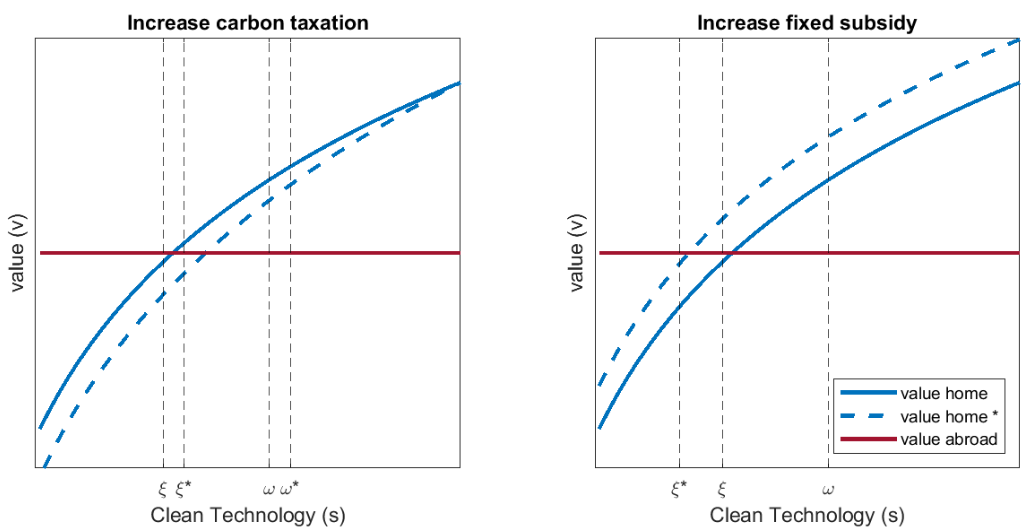

Figure 2: Government policy tools

Graphical depiction of the policy tools employed by the home government. The red line shows the expected value of the home firm if it were to relocate abroad (v^f), while the blue line gives the value of the firm in the presence of a carbon taxation $v(s:\zeta,\kappa)$. The line ξ demonstrates the cutoff value at which firms become indifferent between investing and moving abroad. This line is k_ξ away from the intersection of v_f and v. the thresholds line ω shows the moment at which $\Delta v = k_\omega$. All firms that are on the left of the thresholds ξ and ω move abroad or invest in clean technology respectively. An increase in ζ shifts the value of the firm from $v \to v^*$ in (dashed line) and subsequently pushes the decision thresholds to the right $\xi,\omega \to \xi^*,\omega^*$ (left panel). If governments decide to affect κ, this only affects $\xi \to \xi^*$ in the right panel.

Given their policy tools, the government can increase the price of the carbon taxation as can bee seen in the left panel a of Figure 3. The effect of an increase in ζ can be summarized as follows: $\partial v/\partial\zeta < 0$ and $\partial^2 v/\partial^2\zeta > 0$. Adjusting the value of ζ would raise the threshold at which firms become indifferent between adopting clean technology or not (from ω to ω^*). However, such an increase in ζ would also mean that the threshold for firms to exit the domestic market and move towards a pollution haven increases as well (from ξ to ξ^*). Firms abroad are unaffected by the policy change, i.e. $\partial v^f/\partial\zeta = 0$.

Additionally, the government can increase the number of freely allocated certificates (right panel of Figure 3). The value of this subsidy is benchmarked on the initial levels of the firms and they are therefore independent on the firms decisions. The amount of certificates that each firm recieves reduces at an agreed upon pace. As such, it can be considered to be a fixed cost subsidy κ such that $\partial v/\partial\kappa < 0$ and $\partial^2 v/\partial^2\kappa = 0$. Since it does not affect the marginal value of the firm, it does not influence the investment decisions of the firm directly. It does however affect the decision to move abroad (from ξ to ξ^*). As with the first tool, firms abroad are not affected.

2.3 Productivity differences

This simplistic approach overlooks crucial factor of differences in the level of productivity between firms on the investment decision. One significant oversight is the fact that the burden of the sunk costs of investment is lower for more productive and profitable firms (Forslid et al., 2018). Consequently, these find it easier to comply and abate their emissions. Suppose that, beside clean technology, firms also differ in productivity such that $V(s,z_i,\zeta) > V(s,z_j,\zeta)$ for all $z_i > z_j$. Then, the decision to invest for firms with an equal level of clean technology will therefore be more likely for more productive firms. Both the decision to invest and the decision to relocate are weakly increasing in productivity.

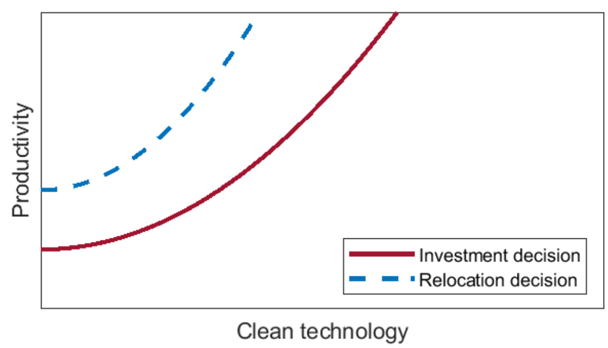

Figure 3: Decision-making matrix

A visual representation of the indifference curves illustrating firm decisions, given a second variable, productivity. Firms situated to the right of the (red) investment indifference curve do not perceive it advantageous to respond to the taxation ζ, either because they are too clean (to right of the indifference curve, or their marginal benefit is too low (below the curve)or because their marginal benefit is insufficient (lying below the curve). In cases where firms are excessively polluting and possess the means to cover the associated relocation expenses, they may opt to relocate (as indicated by the blue curve). Similar assessments regarding this indifference curve are applicable.

To facilitate interpretation of the, I construct a 2-dimensional graph where the indifference curves between both decisions are shown. More productive, polluting, firms are the only ones that find it worthwhile to invest. Conditional on the assumption that the cost of relocation investment, less productive polluting firms find it too costly and will decide to exit.

The figure already hints towards the distributional effects of both idiosyncratic decisions. As only the polluting firms invest or move abroad, the distribution is slowly converging. In contrast, as $log(q(z,s))$, is weakly increasing in both latent variables. An increase in s only for the most productive firms will increase the variance of output.[9] Appendix A formally demonstrates how the first and second moment of both variables is affected by the taxation and the subsequent endogenous decisions.

2.4 General Equilibrium

To reduce aggregate emission output in the scenario described above, it would be optimal for the government to establish a extremely high variable price for the emission output and equivalent high level of fixed cost subsidy. This would encourage a high number of firms to adopt the new technology and prevent their exit from the domestic economy. However, this abstracts from (i) general equilibrium effects that may distort the equilibrium prices, and (ii) the implications of foreign trade.[10] To address these additional concerns, a comprehensive equilibrium model is required, which will be discussed in Section 4.

3. Data and empirical validation

Prior to quantifying the impact of carbon policies on firm performance, it is essential to understand the mechanisms behind the investment decisions. The mechanisms laid out in the previous section suggest that only large, polluting firms find it worthwhile to invest in clean technology and even more so when the price of the carbon certificates is high. To see whether this mechanism holds any value in the real world, I empirically test this using yearly administrative firm-level data from all firms that are present in the EU emission trading system.

3.1 Data sources and construction

The analysis uses the European Union Transaction Log (EUTL) as the main data source. The dataset encompasses the yearly emissions for each firm participating in the ETS for the period from 2005 to 2018. In addition to emissions data, financial information for all participating firms is sourced from their annual accounts in the ORBIS database, maintained by Bureau Van Dijk thereby taking into account the considerations posed by Kalemli-Ozcan et al. (2015) on this database. To combine these two main data sources, I rely on the matching procedure in Letout (2022).

The analysis is limited to the manufacturing sector only to ensure the comparability across firms. As the other firms outside of the manufacturing sector are structurally different from the other firms in the ETS, comparing them could lead to biased results. For instance, the full list of firms that abide to the carbon

[9] This is not to say that the carbon policies are the main driver of increasing inequality regarding size, however they might exacerbate the already increasing inequality.

[10] The impact on investment decision and the decision to move abroad for both is a priori uncertain. Full explanations on how these equilibrium effects affect the decision to invest as well as aggregate conditions can be found in Appendix A.

policies contains electric and waste management companies among others, these are firms that do not trade abroad and have no risk of relocating. They are considered different for the government as well and have received less carbon certificates. The aforementioned mechanism is therefore not applicable for these firms.

Throughout this analysis, I touch upon several additional datasources such as the expected price of carbon certificates, patent data, oil and gas prices, and aggregate trade statistics. Data concerning the price thee of carbon certificates, I obtain from THOMPSON REUTERS. An additional data source are the patent data from PATSTAT. Where I follow the classification of green patents from the World Intellectual Property Organization (WIPO) who identify patents based on their IPC code. (International Patent Classification).[11] Trade data from WIOD tables are used for aggregate statistics. A more elaborate explanation on the data gathering process the sourcescan be found in Appendix D.

3.2 An indicator of firm investment

To measure investment in clean technology, I construct a novel indicator $\omega_{i,t} \in \{0, 1\}$, which denotes whether firm i has invested in clean technology in a certain year $t \in 1, \ldots, T$. Although the direct costs of such investments are unobserved, the variations in the outcome variables, emission output $E_{i,t}$ and value added $V_{i,t}$. These variables make the variable Emission intensity $\tilde{s}_{i,t}$ which can be decomposed such that:

$$\tilde{s}_{i,t} \equiv \frac{E_{i,t}}{V_{i,t}} = \frac{q_{i,t}}{s_{i,t}} \frac{1}{p_{i,t} q_{i,t}} = \frac{1}{s_{i,t} p_{i,t}} \tag{4}$$

Where Emissions $E_{i,t} = q_{i,t}/s_{i,t}$,[12] and added value $V_{i,t} = p_{i,t} q_{i,t}$. Emission intensity is inversely related to the level of clean technology $s_{i,t}$ and prices $p_{i,t}$ of firm i. The measure of clean technology captures everything that makes the firm omit fewer emissions, capturing both changes in the input composition as well as the capacity of the firm to not omit. The latter comprises multiple factors, ranging from an electric car park, better isolated homes, or even the ceding of the most emitting plant while the former focuses on the usage of more (or less) polluting inputs. Note that this can also mean the outsourcing of omitting procedures to other entities. Prices are adjusted by the sectoral price deflator to account for price variations across sectors.[13].

Based on the changes in this variable of emission intensity I construct an indicator $\omega \in \{0, 1\}$ that indicates whether a firm invests in clean technology in a certain year akin to Bessen et al. (2019).[14] The

[11] A full overview of the list of green codes can be found at OECD 2015 classifcation paper.

[12] This measure of clean technology nests the abatement activity adopted in Copeland and Taylor (2004) and Shapiro and Walker (2018) among others. However, a significant point of departure in this study is the fact that this paper considers the dynamic nature and associated costs of adjusting the level of clean technology in this framework, i.e. $s_{i,t+1} = f(s_{i,t}, \ldots)$.

[13] Depending on the type of market conduct, the prices might affect the relationship between the variable of emission intensity and level of clean technology. Perfect competition gives a perfect inverse relationship. However, since these firms are all large and often multinational producers, this market conduct is highly unlikely. Appendix A demonstrates how other types of conduct affect the relationship between the level of clean technology and emission intensity differently

[14] While it shows a lot of similarities with the indicator in Bessen et al. (2023), the setting is different from their indicator. As in this setting, I analyze a major structural shock on the outcome variable while their indicator analyzes shocks in an input variable of capital investment. In this setting I either implicitly assumes that an investment leads to a certain emission reduction decision is, or I examine solely successfully investments. Examining investment decisions this way leaves me with the benefit that I do not have to differentiate between types of investment. I a sense, I leave it up to the firm to be rational thus to decide which type of investment gives them the

development of the investment indicator starts with the premise that investments exhibit a characteristic of lumpiness and persistence. In other words, a significant shock must occur that causing a substantial decrease in the level of clean technology compared to the prior state. The investment decision can be denoted as follows:

$$\omega_{i,t} = \mathbb{1}\underbrace{\{(1+\lambda)\tilde{s}_{i,t+1} \leq \tilde{s}_{i,t}\}}_{\text{Transitory state}} \underbrace{\left\{(1+\lambda)\frac{1}{B}\sum_{b=1}^{B=2}\tilde{s}_{i,t+b} \leq \frac{1}{W+1}\sum_{w=0}^{W=2}\tilde{s}_{i,t-w}\right\}}_{\text{structural state}} \tag{5}$$

The investment indicator can be decomposed down into two components. The *transitory state* governs the fact that there is a shock in Emission intensity from time t. The shock must exceed the arbitrary threshold value λ. This ensures the lumpiness of the clean technology investment. The *structural state* ensures the absorption of clean technology into a new state that is persistently lower than the initial state. In other words, the average emission intensity the next 2 years should be at least 20% lower than the average of the previous 3 years. The investment indicator equals 1 if both conditions are met. As a threshold, the percentage change between these two states is set to be $\lambda = 20\%$. Figure 4 demonstrates that firms have invested throughout the sample. The firms have invested a bit more at the beginning of the period, which could point towards the fact that they solely invested in low-hanging fruits, but on average they invested the whole time. Moreover, the investment decision seems to be correlated with the carbon price, which might suggest that firms invest more when the price is high.

It is important to acknowledge that this indicator is not free from bias. Its accuracy depends on both the functional form of the indicator and potential errors in measuring the underlying variable, emission intensity. To address the issue of functional form, I apply several variations of the indicator in Appendix D. Specifically, I estimate the current indicator using different cutoffs for λ at 10%, 20%, or 30%, along with varying parameters for the structural state B and W. If the investment threshold λ is set too low, it might inadvertently capture fluctuations in productivity. Conversely, if λ is set too high, it risks missing out on certain investments in clean technology altogether. Further, A higher value of B and W ensures that the shock is more structural, but at the cost of observations. I look at the period after and before the parameters constrain the evolution of emission intensity, and there does not seem to be a significant upwards trend afterwards. Additionally, variations in the transitory state are introduced to ensure that the results are not influenced by the manner in which the shock occurs. The results in the appendix remain consistent with the mechanism discussed in the previous section.

To validate its status as an indicator of investment, the indicator should also manifest in the data on capital investment, a moment which is not targeted in the construction of the data. In Appendix D, an analysis is conducted on all firms that have undertaken a clean technology investment at least once, with the investment period normalized to 1. The periods before and after the investment decision for capital and various other variables are examined. The investment decision is associated with a structural increase in

biggest reduction in emission output.

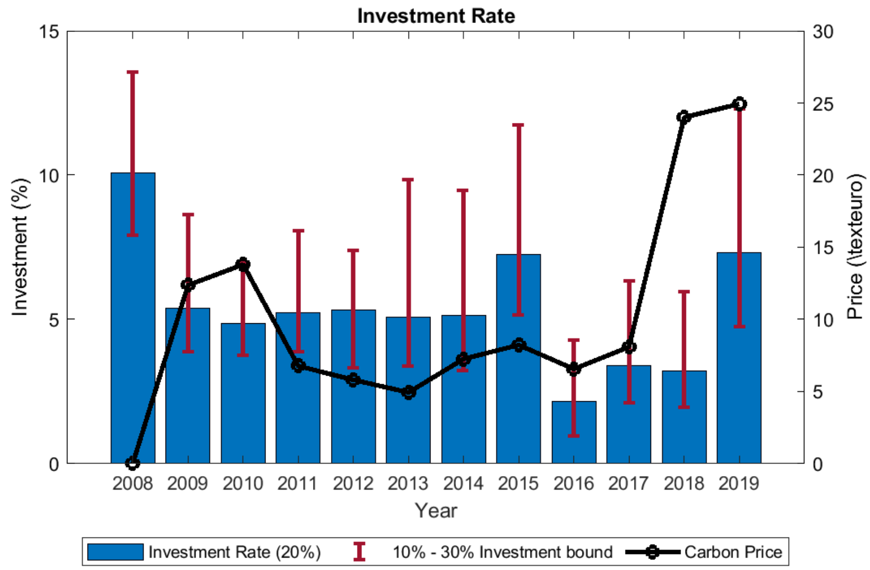

Figure 4: Yearly investment rate

The share of investment by year. The first 3 years (that align with phase 1 of the EU ETS), are used to set up a baseline of the clean technology level. The investment indicator is constructed using Equation 5 with a cutoff λ of 20%. Correlation of this investment indicator with the price of carbon certificates is around 10%.

capital of approximately 20%, measured as fixed tangible assets, as well as an increase in value added and a decrease in emissions. Other variables appear to remain largely unaffected by the investment decision. This indirectly also targets the notion that changes in emission intensity is solely driven by volatility in output.

Finally, even after deflating by the industry price, changes in the emission intensity might still be driven by price fluctuations though omitted price bias. The price can be affected by within-firm structural changes, which can either be driven by changes in clean technology s or productivity z. The latter term can be interpreted loosely as it incorporates both changes in demand/quality as in actual productivity of the firm. DechezleprÃªtre et al. (2018) argue that the pass-through of the ETS policy is substantial. Price changes resulting from shifts in the firm's clean technology level could introduce an upward bias, an issue easily rectified by raising the investment threshold (λ). In contrast, other changes in the state of the firm are not that clear to solve. To safeguard against this, I follow the literature on production function estimation and control for other covariates and analyze various subsets of firms (e.g., excluding those exiting the sample) to see how this biases the investment decision (Van Beveren, 2012).

3.3 Summary statistics

The empirical analysis exploits information on firm decisions across two groups, firms that invest at least once throughout the duration of this sample (*Investors*) and those that do not (*Non-Investors*). The upper panel of Table 1 presents the summary statistics for the main variables of interest in the last year of phase 1 in 2007, the initiation period. Approximately 1/3rd of firms in the taxation system has at least invested once since the the system was rolled out. Interestingly, these investors are larger in terms of employees, and turnover and they pollute more as compared to the non-investors. Nevertheless, these average statistics hide the extreme heterogeneity between the two subgroups. the 10th and 90th percentile reveal that both subgroups have many large firms with more than 1000 employees and at the same time have smaller SMEs with less than 100 employees. Similar magnitudes are at play for turnover and emission intensity.

Table 1: Summary Statistics

Levels 2005 - 2007

	Investors			|	*Non-Investors*		
Variable	Mean	p10	P90	|	Mean	p10	P90
Employees:	1179	33	2253	|	591	25	1246
Value Added :	144.8	1.6	238.3	|	51.2	0.8	213.7
Emissions :	106.5	0	184	|	59.5	0	86
Emission intensity*:	0.49	0.01	1.47	|	0.52	0.01	1.24
Number of firms:	2405			|	4744		

Growth 2007 - 2018

	Investors		|	*Non-Investors*	
Variable	Differences	Percentage	|	Differences	Percentage
Employees:	−129	−11%	|	78	13%
Value Added:	13.0	9%	|	15.4	30%
Emission intensity:	−0.1	−29%	|	−.002	−6%
Firm exit:	79	0.35%	|	317	1.09%
Patents:	174	7.2%	|	268	5.6%

Summary statistics for the sub-sample of firms in the manucfacturing industry (NACE 2. REV 2. 10 - 33) that invest at least once throughout the span of the dataset (*Investors*) and those that never invested (*Non-Investors*). Entrants are excluded. The upper table shows the average, 10th and 90th percentile for the 2 sub-samples at the beginning of the taxation scheme in 2007. Turnover is deflated with sectoral prices and expressed in million euros. Allocated certificates are expressed and thousands respectively. The lower panel shows the growth from 2007 to 2018 in levels and percentages - the latest for which the investment indicator is available - in levels and percentages. The variable carbon leakage denotes whether the firm operates in a sector which the EU denotes as prone to carbon leakage. Percentages for firm entry and exit are relative to the total observations. Percentages for patents are relative to the total number of firms for each type of firm.

The lower panel of Table 1 shows the growth of the two subgroups of firms from the beginning of the taxation scheme to 2018. Interestingly while the employment of both groups remains relatively the same to their level in 2007, the growth is highly visible both in turnover with an increase of more than 50% for the investors. At the same time, Investors are able to reduce their emission intensity by 20% on average. These variables indicate that certain firms are able to better capitalize on the taxation scheme, while others remain behind. Lastly, the economy surrounding the emission transaction system is not dynamic on the extensive margin. Entry and exit are both extremely uncommon relative to the aggregate economy.

These statistics provide a first impression of the firms investing in the EU ETS and demonstrate that there are significant differences, both in levels at the beginning of the policy in 2007 and in the growth from 2007 to 2018. It is important to note, however, that these differences are not conditional on other confounding variables. To see which variables are a driving predictor of being an investor, a more elaborate statistical method is needed.

3.4 Empirical validation

This section establishes a relationship between carbon taxation and increased investments in clean technology. Before the construction of a model to examine the long-term structural impact of the carbon taxation, it is first necessary to validate the mechanism as explained in Section 2. Additionally, these results serve as out-of-sample moments to confirm the calibration of the structural model.

The mechanism laid out in Section 2 starts from the presumption that firms that invest in clean technology are on average more polluting and larger than their non-investing counterparts. To verify whether this holds true in the data, I compare the characteristics of investors prior to their investment with those that decide not to invest. In practice, I apply two regressions. One to see whether the firm invests in phase II (from 2008 to 2012) based on their average conditions in phase I (from 2005 to 2007) and whether the firm invests in phase III (post 2012) given their characteristics in the period from 2011 and 2012. I employ a linear probability regression of the following form:

$$I^t = \beta lnV_{i,0} + \eta ln\tilde{s}_{i,0} + X'\alpha + \delta_{s,c} + \varepsilon_{i,0} \quad (6)$$

where the dependent variable $I^t \in \{0,1\}$ indicates whether the firm engages in at least one investment ($\omega = 1$) in clean technology in the following t years, i.e. $t \in \{2008-2012, 2013-2018\}$. $V_{i,0}$ and $\tilde{s}_{i,0}$ represent the average initial level of value added and emission intensity for each firm respectively, and γ and β are their (linear) elasticity on the probability to be an investor. The composite variable X includes other variables of interest such as the share of freely allocated certificates. The error terms are clustered at the sector-country level, and $\delta_{s,c}$ are sector-country-fixed effects.[15]

Table 2 documents the baseline results the decision in phase II, phase III and the decision to exit for multinational firms. Firms that invest in clean technology are on average larger and have a higher level of emission intensity. This result supports the idea that the decision is an investment decision where more

[15]Country fixed effects are essential in this specification. There exists substantial heterogeneity between countries in their approach to the taxation of carbon and sub-sequentially as well in their firms responses to the policy. For instance, some countries like Sweden have additional carbon policies alongside the ETS, while others like Belgium are more concerned about relocation threats and thus subsidize their firms. A comprehensive overview of countries and their respective investment rates can be found in Appendix D. Nevertheless, it is noteworthy that the ETS system is the most comprehensive and stringent across all these countries.

Table 2: Firm characteristics

	(1) $I^{<2012}$	(2) $I^{>2012}$
ln_Emission_intensity	0.049***	0.046***
	(0.009)	(0.010)
ln_va	0.038***	0.054***
	(0.010)	(0.011)
ln_allocated	-0.014	0.002
	(0.013)	(0.015)
Adjusted R-squared	0.065	0.098
Observations	1950	2037
Country-Sector F.E	✓	✓
Clustered S.E.	C-S	C-S

Baseline results for the effect of the price of carbon emissions on the investment decision. Standard errors are clustered at the country-sector level for the investment decision and in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Specification (1) and (2) respectively display the probability to invest for firms before 2012 (post 2012) based on their average characteristics from 2005 to 2007 (2011 to 2012). I include only a balanced panel without entry and exit.

polluting firms catch up.[16]

An equal regression is conducted to analyze the characteristics of firms that are part of a multinational and decide to exit throughout the sample. I limit the sample to only include international multinational firms (i.e. firms that have a headquarter that is not in the same country as their origin) as carbon leakage within firms most likely occurs through these firms (Borghesi et al., 2020; DechezleprÃªtre et al., 2019). There are 878 firms that can be considered as such, of which 36 have decided to exit during this period. Standard errors are bootstrapped due to the small sample. The regressions analysis demonstrates that a higher share of freely allocated certificates does increase the likelihood for these firms to exit, suggesting that the government has indeed tried to reduce that probability, and maybe even prevented worse.

To see whether firms internalize the imposed taxation in their investment decision rather than invest for other reasons, I conduct a second regression analysis to examine the probability of investing. It is already known that carbon taxation affects the performance of firms in the short term (DechezleprÃªtre and Sato,

[16]This is in stark contrast to what is often assumed in models that model the innovation process where there is a divergent pattern where clean firms find it easier to innovate more and it's extremely costly for polluting firms to switch (Acemoglu et al., 2016). Additional results in Appendix D examine patenting decisions by investors and find that most of these firms do not innovate and there is little difference between investors and non-investors in their innovation decisions. In fact, most patent applications in green technology are done by firms that do not operate under the ETS framework. This latter would potentially point towards an 'innovation' industry that sells their new products to these polluting firms (Atkeson and Burstein, 2010). To further ensure the robustness of the distinction between innovators and innovation, I explore all patents related to green technology (as per OECD classification) filed with the EPO. Merely 8% of all ETS-participating firms have subsidiaries or sister firms that have claimed at least one patent in this domain. Hence, the majority of firms reducing their emissions have opted for alternative strategies, such as investing in existing machinery and products. Finally Appendix D also demonstrates that The share of freely allocated certificates does not seem to be internalized in the firms investment decision in the phase III, confirming the notion that since it is ex-ante determined it can be seen more as a fixed cost subsidy.

2017; Martin et al., 2016) and that more emission-intense firms are more significantly prone to an increase in this taxation. However, it is unclear whether they internalize the price as well in their investment decision. I analyze the extent to which the price of carbon has a higher impact on more emission-intensive firms with the following linear probability model:[17]

$$\omega_{i,t} = \beta \ln(\tilde{s}_{i,t}) + \phi \ln(\tilde{s}_{i,t}) \ln(\zeta_t) + \iota_{c,t} + \tau_{s,t} + \delta_i + \varepsilon_{i,t} \tag{7}$$

where the yearly decision to invest $\omega_{i,t}$ depends on emission intensity $\ln(\tilde{s}_{i,t})$ interacted with the price of carbon ζ_t. The variables $\iota_{c,t}$, $\tau_{s,t}$ δ_i denote sector-time, country-time and firm fixed effects respectively. The findings in Table 3 suggest that firms primarily consider price of carbon certificates, revealing the importance of the ETS as a driving mechanism of the investment decision. The elasticity ϕ should be interpret as conditional to emission intensity $\varepsilon = \phi * \ln(\tilde{s}_{i,t})$.

Table 3: Signalling function price

	$\omega_{i,t}$	$\omega_{i,t}$	$\omega_{i,t}$
ln_price	0.002***	0.002*	0.002***
	(0.001)	(0.001)	(0.001)
ln_oil_price			-0.003
			(0.622)
Non_market_EPS		0.000	
		(0.962)	
Adjusted R-squared	0.109	0.110	0.109
Observations	22,230	22,230	22,230
Country-Year F.E	✓	✓	✓
Sector-Year F.E	✓	✓	✓
Firm F.E	✓	✓	✓
Clustered S.E.	Firm	Firm	Firm

Baseline results for the effect of the price of carbon emissions on the investment decision (Equation 7). Standard errors are clustered at the firm level and in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Data spans from 2008 to 2018. The investment indicator $\omega_{i,t}$ is constructed following the procedure in Equation 5. Specification (1) denotes the importance of the price of carbon price. Specification (2) compares to other non-market environmental protection regulation with the inclusion of the OECD country-specific EPS-indicator. Specification (3) compares with changes in (environmental) market-based dynamics through the inclusion of the aggregate oil-price. Other specifications and robustness tests can be found in Appendix D

In sum, the empirical section validates the mechanism laid out in Section 2 and predicts that firms that

[17] Estimating the price elasticity of investment decisions requires a more sophisticated approach than a simple Ordinary Least Squares (OLS) framework due to the inherent endogeneity problem in supply and demand models. During periods of good economic conditions, firms typically increase production, which increases profitability and makes them more inclined to invest. However, this also indirectly contributes to elevated carbon prices, which would further increase investment. Consequently, interpreting the influence of price on investment decisions in isolation is not feasible.Moreover, a higher price of carbon might affect the cost of the investment, as it is an indirect indicator of the necessity of the good which is visible to the supplier of the investment good. The question of who reaps the benefits from the carbon taxation investment is not answered in this paper. To address this complexity, I add year country-year-sector fixed effects accounting for the aggregate economic performance of each sector in a given year t and interact emission intensity $(\tilde{s}_{i,t})$ with the logarithm of the carbon price (p_t), and other macroeconomic prices such as the aggregate oil price. for the non-market EPS variable, I keep the value. This limits the analysis as I can only make statements relative to the average emission-intensive firm. To facilitate interpretation, emission intensity is standardized to a standard deviation of 1.

invest in clean technology are, on average, larger and pollute more than those that do not invest. They also demonstrate that firms internalize the price of carbon taxation in their investment decision. However, the reduced form analysis cannot inform about how the aggregate conditions have been affected through the introduction of the carbon policy. To answer this, a more elaborate structural model is needed.

4. Structural model

To assess the overall impact of environmental regulations, I construct a structural model of firm dynamics that builds upon the seminal papers of Melitz (2003) and Atkeson and Burstein (2010). The model will be used to examine the transition dynamics and the implementation of clean technology over time. Time is discrete, and each period is labeled as $t = 0, 1, 2, \ldots$. The economy has 2 countries: home and foreign; variables in the foreign country are denoted with a f. The main focus of this analysis will be on the economy of the home country.

Production in the home country is structured as follows. A continuum of heterogenous firms that are monopolistically competitive and can trade internationally produce a good given their production technology and level of clean technology. They are constrained by a taxation on their emission output which they can reduce either by investing in clean technology or relocating to the foreign economy. Firms in the foreign country are exempted by the policy and their production is only affected indirectly through changes in the aggregate prices. The investment and relocation policies as well as aggregate prices and outputs are determined endogenously through the intratemporal market clearing across countries.

Growth in the economy is balanced in the absence of emission taxation. When the home government decides to implement the taxation, the economy triggers a transition to where emission output will eventually be reduced to zero. Productivity evolves at a constant rate $z_{t+1} = \gamma z_t$, equal for all firms.

There is a constant mass of firms active in each country, normalized to 1. A firm in the home country with state variable $\lambda_t = (s_t, z_t)$ has a constant level of productivity equal to $exp(z_t)^{1/(\eta-1)}$ and produces output q_t with labor l_t as the sole factor of production with a constant returns to scale production technology:

$$q_t = exp(z_t)^{1/(\eta-1)} l_t \tag{8}$$

The output of the firm can be used for final demand, either in the home country (q_d) or exported to the country abroad (q_x). Exports are subjected to a iceberg type cost τ which is expressed in terms of the output good.

Firms are constrained in their marginal cost $Wc(s_t; \zeta_t)$ where wages for the home country are set as the numÃ©raire. The latter term is a function of the price of emission output ζ_t and the firms individual level of clean technology s_t constitutes the following functional form $c \equiv (1 + \zeta_t / s_t) > 1$, essentially creating a wedge between optimal output and actual output common to the literature of the misallocation of resources (Hsieh and Klenow, 2009; Restuccia and Rogerson, 2008), but in this setting all firms can endogenously decide to reduce their carbon output.

4.1 Clean technology adoption

Firms operating at home can choose to invest ($\omega = 1$) and pay a cost k_ω to receive an updated clean technology or do nothing, normalized to zero. The cost of the investment is independent of current level of clean technology. The aggregate distribution of clean technology is denoted as$s \sim \mathscr{S}(s) \in]0, \infty)$. There is no uncertainty regarding the acquisition of the investment good such that the step-size increase $\chi > 1$ is known to all firms. To keep the model tractable, I simplify the step-size increase of the adoption of the improved clean technology to χ, constant across all firms.[18] Adopting a new technology will increase the level of s_t and thereby decrease the marginal cost of the firm:

$$s_{t+1} = \begin{cases} s_t\chi & \text{if } \omega = 1 \\ s_t & \text{if } \omega = 0 \end{cases} \tag{9}$$

Firms can choose to invest ($\omega = 1$) into the clean technology and receive a new level of clean technology $s\chi$ by paying a fixed cost $k_{\omega,t}$. The cost of the adoption of the new clean technology evolves at a rate $k_{\omega,t} = \gamma k_{\omega,t-1}$. Modeling the adoption of clean technology in the following manner involves two implicit assumptions. Firstly, it assumes that all firms that produce the clean technology good produce in perfect competition where the stock of ideas is universally known and evolving at a constant rate γ, such that the price of the good is inversely proportional. In a further section of the paper this assumption will be relaxed. Secondly, it operates under the assumption of perfect substitutability in the ideas market, where all ideas are considered equally feasible and costs are uniform.

4.2 Trade

In this model, the demand for goods comes from 2 countries $g \in \{F, H\}$ The following set of equations will be expressed from the perspective of the firm in the home country, which is prone to the government taxation. Unless stated otherwise, these equations are also applicable for the firms active in the foreign country. I assume that countries are symmetric in the distribution of productivity for operating firms. As the price-setting problem is completely static, I abstract away the time index t in this section of the paper. The asymmetry between countries arises solely from the differences in the policies enacted by the home government to improve the environmental performance of firms, variable ζ and fixed κ.[19]

[18] It is worth noting that the purchase of a new clean technology is characterized by a high level of certainty on its emission output, such as the acquisition of new filters or cleaner machines for instance, Consequently, there would be much less uncertainty associated with the investment decision in this model.

[19] Note that this indicates that in a steady balanced growth state, where $\zeta = 0$ for the home country, the countries are symmetric and consequently, trade balance is secured. During the transition, I assume no trade balance, and thus for aggregate wages W_g not to adjust, for the trade in this emission intensive industry is only a subset of the total economy. This causes differences in prices, and enables the decision for firms in the home country to relocate abroad. In a later stage of the model, the difference between countries will also include differences in marginal costs $W \neq W^f$

The output produced in the home country can either be used domestically or exported to the foreign country.[20] Engaging in the former type of trade involves an extra iceberg-type trade cost ($p_x = \tau p_d$) The price-setting of each firm is static.

$$p_d = \frac{\eta}{\eta - 1} \frac{W_g c(s;\zeta)}{exp(z_t)^{1/(\eta-1)}} \tag{10}$$

The trade cost τ is symmetric across countries. Note that firms operating in the home economy also incorporate the policies ζ in their price-setting for the exporting market and are thus asymmetric to the foreign country. In the foreign country the added taxation converges back to 1 $c(s,\zeta) = 1$.

Demand in the home country is a function of the charging price such that $q_h = p_h^{-\eta} P_h^{\eta} Q_h$, where Q_h and P_h denote the composite aggregate demand for the home country and the associated price index respectively. Given the demand for each variety in the home country, variable profits are given by $\pi_h = \max_l p_h q_h - W_g c(s;\zeta_g) l_h$. The demand for the exported good depends on the aggregate foreign price $q_x = p_x^{-\eta} P_f^{\eta} Q_f$.

Finally, the home government hands out fixed subsidies subsidies κ, both to domestic firms and to subsidiaries by firms from the foreign country, to encourage firms to keep their production at home and not relocate when the taxation ζ becomes more stringent. Total static profits are a function of the domestic profits and profits from the foreign market and can be summed up to $\pi(\lambda) = \pi_d(\lambda) + \pi_x(\lambda) + \kappa$.

4.3 Exogenous growth

The primary focus of this model is on how firms behave during the green transition. Consequently, it is essential to examine the evolution of the state variables in greater detail.

This model deviates from a balanced growth model for one main reason: over time, the cost of investing in green technology decreases relative to the aggregate labor cost. The aggregate price index, which depends on productivity, increases by γ. As the budget spend to this sector, I, remains constant, the corresponding aggregate goods basket has to decrease at a similar rate. The prices of sunk costs, expressed in terms of the input variable labor, remain constant, except for the investment good, which also decreases by γ. In Section 6, this assumption will be relaxed, following Acemoglu et al. (2016) by applying a separate endogenous parameters for both evolutions. In addition to the decreasing cost of green technology, the model allows the price of carbon emissions, ζ, to vary over time, mirroring the evolution of the carbon price in the EU ETS system. However, this evolution is not structural.

4.4 Value function

To formulate the firm decisions, we turn towards the dynamic recursive version of the model. Firms maximize their present value V_t^g of lifetime profits. I start by examining the value function of firms operating at home $g = h$. Each period firms can endogenously select to stay in the home country or pay a fixed cost of k_ξ and relocate abroad. By moving abroad, they can avoid being subjected to the government's policies.

[20]Note that in the firms that participate in the EU ETS framework are large and they are often present in a sector that is commonly traded internationally, thus the firms in this industry are very likely to export.

Firms opt to stay in the home country select optimize their static profits given the aggregate prices, and determine whether or not to invest in clean technology ω. to reduce the burden of the taxation. The future returns are discounted by the discount factor $\beta \in (0,1)$.

$$V_t^h = \max\{V_t^{h*}(\lambda), V_t^f(\lambda) - k_\xi\} \tag{11}$$

$$V_t^{h*}(\lambda) = \pi_t(\lambda) + \max_{\omega_t \in [0,1]} \beta \int_\lambda \left\{\omega_t(V_{t+1}(\lambda') - k_{\omega,t}) + (1-\omega_t)V_{t+1}(\lambda)\right\} G(d\lambda) \tag{12}$$

Where λ' denotes the new, update state variable after the investment decision $\omega = 1$. The value function of firms that operate in the foreign country equates $V_t^f(\lambda) = \pi_t(\lambda) + \beta \int_\lambda V_{t+1}^f(\lambda)G(d\lambda)$. Firms abroad cannot further improve their levels of clean technology nor relocate.

4.5 Aggregation and market clearing

4.5.1 Distribution of firms

The distribution of firms can be summarized over their 2 state variables, the exogenous productivity and their (endogenous) level of clean technology $\lambda_t = (z, s_t)$. The measure of incumbents is the sum of the firms active in the home economy and the foreign country, an can be decomposed in $\int \mu(\lambda) = \int \mu_h(\lambda) + \int \mu_f(\lambda)$. The distribution of firms in the home country follows the following motion:

$$\mu_h(\lambda_{t+1}) = \int_\lambda F(s_{t+1}|\lambda_t)\mu_h(\lambda_t)G(\lambda) \tag{13}$$

where the transition operator $F(s_{t+1}|\lambda_t)$ describes the transition law for the underlying variables z and s, along with the decision to move abroad. it is thus given by $F(s_{t+1}|\lambda_t) = (1 - \xi_t(\lambda_t))R(s_{t+1}|\omega_t(\lambda_t))$ with $\xi_t \in [0,1]$ and $\omega_t \in [0,1]$ signify the decision to move abroad and invest in clean technology respectively. The conditional distribution R represent distribution after the investment decision. Note that, since the model is in a state of transition, the decision functions depend on time.

The evolution for firms in the foreign country is different from the home country in two major ways. First, firms in this setting cannot move to the home country and are destined to stay here. Instead, the evolution in the foreign country is characterized by an influx of firms from the home country seeking to avoid the taxation. Second, the transition law does not depend on the investment decisions since $\omega = 0$ as long as $\kappa, \zeta = 0$. The full equation is given by:

$$\mu_f(\lambda_{t+1}) = \int_\lambda H(s_{t+1}|\lambda_t)[\mu_f(\lambda_t) + \mu_h(s_{t+1}|\lambda_t, \xi = 1)]G(\lambda) \tag{14}$$

where the function $H(s_{t+1}|\lambda_t)$ describes the transition law for the distribution of firms operating in the foreign country. As long as the . If both are considered are considered to be zero, such as in the benchmark model, firms do not invest and the function boils down to a standard identity matrix. The equation also includes the influx of firms evading the taxation from the home country, (where $\xi_t = 1$) denoted by the second term $\mu_h(s_{t+1}|z, s_t, \xi = 1)]$.

4.5.2 Market clearing and aggregation

The clearing conditions in this model are threefold. First, their is the budget clearing from the home government. The home government generates revenue through the taxation of the emission output, denoted as ζ, and aims to maintain a balanced budget. They reinvest this revenue and allocate a fixed subsidy, κ, lump sum, to all firms that operate in the domestic market in order to reduce the risk of firms relocating abroad.

$$\int_\lambda \frac{\zeta q(\lambda)}{s} \mu_h(\lambda) G(\lambda) = \int_\lambda \kappa \mu_h(\lambda) G(\lambda) \tag{15}$$

Finally, As the emission sector is only a part of the aggregate traded goods, I assume no trade balance. This leaves me with 2 the market clearing conditions - for the aggregate goods and price indices.

Each period the market of the aggregate good clears $Q_D = Q_S$. The total amount of the aggregate good basket supplied to each country can be represented as:

$$Q_D = \left[(Q_h^{dom})^{\frac{\eta-1}{\eta}} + (Q_x^{for})^{\frac{\eta-1}{\eta}} + (Q_f^{for})^{\frac{\eta-1}{\eta}} + (Q_x^{dom})^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \tag{16}$$

Where the first part of the equation are the goods produced in the home country signifies the goods produced domestically for domestic demand $(Q_h^{dom})^{\frac{\eta-1}{\eta}} = \int_\lambda q_d(\lambda)^{\frac{\eta-1}{\eta}} \mu_h(\lambda) G(\lambda)$. The second part of the equation aggregates the quantity that is imported from abroad $(Q_x^{for})^{\frac{\eta-1}{\eta}} = \int_\lambda x(\lambda) q_x(\lambda)^{\frac{\eta-1}{\eta}} \mu_f(\lambda) G(\lambda)$. The third and forth part are equivalent but for demand in the foreign market.

The prices during each period t are expressed in relation to the wages in their respective country for that particular period, which is normalized to a value of one in both countries. Akin to the total demand, the aggregate price index for the home country can be summarized as:

$$P_h = \left[(P_h^{dom})^{1-\eta} + (P_x^{for})^{1-\eta} + (P_f^{for})^{1-\eta} + (P_x^{dom})^{1-\eta} \right]^{\frac{1}{1-\eta}} \tag{17}$$

Where the price of all domestic producers can be decomposed akin to the goods market clearing. The first part denotes the prices of the goods produced domestically $(P_h^{dom})^{1-\eta} = \int_\lambda [p_h^{dom}(\lambda)]^{1-\eta} \mu_d(\lambda) G(\lambda)$. The second part of the equation denotes the price index for the imported goods from producers active in the foreign country $(P_x^{for})^{1-\eta} = \int_\lambda x(\lambda) [p_x^{for}(\lambda)]^{1-\eta} \mu_f(\lambda) G(\lambda)$.The third and fourth part of the equation are the same but for the demand in the foreign market.

4.6 The EU ETS

4.6.1 The carbon price evolution

The primary objective of this research project is to conduct a quantitative examination of the impact of carbon policies on the aggregate economy. To do so, I model the introduction of this policy as exogenous. More specifically, I feed the path of the carbon price ζ and accompanying carbon subsidy κ as the driving process into the model. The economy starts in a steady state at phase 1 from 2005 to 2007 as those years are necessary in the construction the indicator of firm investment, This choice is motivated by the low carbon price and an underdeveloped secondary market during this period. The primary focus of the model is on analyzing the transition from the introduction of phase 2 in 2008 to the year 2018 and how the distribution of firms has shifted throughout.

Every period, the price of the investment good k_ω reduces by a constant value γ, making it cheaper for firms to invest. At the same time, the price of carbon emissions ζ_t fluctuates, but it is known to all firms. At the beginning of each period, firms endogenously form their dynamic decisions on whether to invest in clean technology or relocate abroad given the future values $\{\zeta_{t+1}, ...\zeta_{t+...}\}$. The firms static profit maximization where they set current prices and output is done given the actual price of carbon ζ_t. As time progresses to the next period, firms observe the new ζ_t and reevaluate their decisions again.

The price of carbon certificates evolves according to the yearly spot price ζ in Figure 4. I set the price in the future to 48 to match the social cost of carbon common to the literature.

In the subsequent section, I compare the benchmark model with two alternative scenarios to highlight the significance of indirect effects influencing firms in their investment decisions. Firstly, I introduce a scenario where the prices remain constant and the goods market does not clear. This makes that firms are not affected though the feed-back effect of other firms. In this setting, firms are notably less responsive to changes in the tax system, as consumers lack the ability to substitute. The second scenario emphasizes the importance of trade for firms to base their investment decision on. More specifically, firms in the home country operate in autarky and do not compete with firms in the foreign country, but they experience the competition with firms in in the home country though the goods market clearing constraint. The increased competition in trade would put severe additional downward pressure on the aggregate price index which in turn would hamper the profit margins of home firms.[21]

4.6.2 Accompanying parameters

Before solving the model, I will choose a conventional value for the elasticity of demand, $\eta = 6$, and set the discount factor to $\beta = 0.98$ such that it matches a yearly interest rate of approximately 2% during this time. I set the yearly evolution parameter $\gamma = 4.5\%$ To match the yearly increasing trend of aggregate real output in Figure 1 from 2005 to 2018.

[21] Appendix A shows that it is a priori unclear how firms would respond to these indirect margins.

To measure the symmetric cross-border trade costs τ, I use the Head-Ries index (Head and Ries, 2001) and consider the European Union as the 'home' country, more specifically I include all countries that are either part of the EU ETS or part of the European Union. and the rest of the world as the 'foreign' country. The index uses the observed values of bilateral trade flows relative to the the domestic absorption to infer the cross-border costs. Appendix E discusses this in more detail. Trade between countries is almost as 3 times as expensive with the parameter τ equal to 2.91.

The calibration procedure nests the calibration of the model in the steady state from 2005 to 2007, prior to the second phase of the ETS system, and simulation of the transition from this steady state to 2020.

I first quantify the state variables in the steady state situation of phase 1. In particular, the values regarding the distribution of firms are determined prior as the investment decision can still be considered absent. This simplification makes that the informative moments in the data are almost one to one applicable to those in the model. The initial steady state moments are indexed by zero.

The initial distribution of the idiosyncratic firm productivity are set to match the variance of value added prior to the implementation of the taxation. From the demand assumption of the model, I can back out the variance of productivity as the variance of real output given the elasticity of demand $\eta = 6$:

$$var(z_0) = \frac{1}{\eta^2} var(\log(q_0))$$

The data yields a variance of output of 1.9 which translates into a variance of productivity of 0.31.

The parameters governing the distribution of clean technology are set to match the standard deviation of emission intensity in the data $\mu_{s_0} = -6.4$ and $\sigma_{s_0} = 1.84$. The joint distribution of both productivity and clean technology is set to mirror a correlation between real output and emission intensity, denoted as $corr(s_0, log(q_0)) = corr(s_0, z_0) = -0.25$.[22,23] The correlation between real output and emission intensity in the data is conditional on the country and sector the firm operates in.

Table 4: Calibration Transition model

Parameter:	Value:	Moment:	Model:	Data:
k_ω	0.25	Domestic Investment rate	0.078	0.078
k_ξ	2.96	Domestic Multinational exit rate	0.004	0.006

The table presents the moments that are matched in the simulated model with their empirical counterpart between 2008 and 2018. It shows thee value of the underlying parameter as well as the moment on which the respective parameter is matched and their value in both the data and the model.

Finally, I calibrate the two remaining parameters k_ω, k_ξ to match their individual informative moments during the transition. The data concerning the cost of the endogenous decisions is not available, however the database can indicate the occurrences of the decision to invest for each firm. The cost of investment, k_ω,

[22]The observation that larger firms are already cleaner on average might be attributed to factors such as input composition - as larger firms are often deemed more capital-intensive- or the presence of smaller other policies that have had an influence prior to the EU ETS, which have already influenced their level of clean technology.

[23]More information regarding the relation between q and z in the calibration of the steady state model can be found in Appendix E

matches the the share of investment occurrences in the data. Similar to the cost of investment, the cost of moving abroad k_ξ is matched by the fraction of multinational firms that exit the economy. A summary of the parameter values and their informative moments is given in Table 4. The costs are expressed in wages of the domestic country.

5. Transition dynamics

In this section, I first document that the model can generate satisfying outcomes that resemble those observed in the data, where I compare the regression results in Section 3 with those from the model. Subsequently, I explore the impact of investment decisions in clean technology on aggregate emissions and welfare. To dissect the indirect effect of the investment decisions, I contrast the benchmark model with two alternative models: a model lacking the trade channel and a model without any general equilibrium effects. Next, I delve deeper in the firm heterogeneity and explore the unequal product of the carbon taxation on firm-level outcomes.

5.1 Validation

Before using the model for inference, it might be useful to look how well the benchmark model (with trade and general equilibrium effects) can reproduce other facts in the data that are not explicitly targeted. In order to validate the model I compare both aggregate and firm-level moments with the actual data. The aggregate moments I want to target in particular are the reduction of total emissions and the reduction of the average emission intensity. For the firm-level targets, I resume the regressions from the empirical validation on a simulated dataset of 100 000 firms based for the transition from 2008 to 2018 with the benchmark specification.

The Right panel of Figure 5 analyzes the investment rate. Notably, the model tends to overpredict investment decisions during years where the price of carbon is high (i.e. at the beginning of phase 2 and at the last year, 2018). Conversely, it tends to under-predict during periods of lower prices. I attribute these discrepancies to the absence of any additional macro-economic uncertainty in the model. a factor undoubtedly present in the actual data yet omitted to increase the readability of the model. The results do seem to indicate to replicate the elasticity of the investment really well. Next, the left panel Figure 5 compares the reduction in aggregate emissions relative to profitability in the data with that from the model. The model fits the aggregate reduction of emissions relative to the profits very well (aside from the first year).

In Table 5, the results derived from the data are compared with those generated by the model. The model produces outcomes of similar magnitude to the data, evident in both the regression analysis of firm characteristics and the regression of whether the carbon price influences investment decisions. Since there is no additional uncertainty beyond the fluctuations in the carbon price, I have excluded the standard devia-

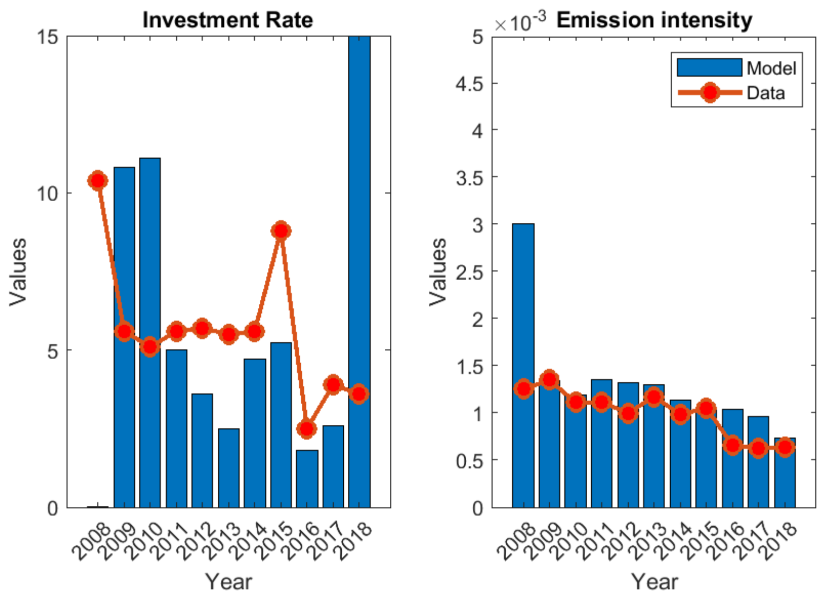

Figure 5: Validation Transition

Comparison between the data (red lines) and outcomes in the model (blue bars) . The left panel shows the (targeted) yearly aggregate investment rate. The right panel shows the evolution of the aggregate level of emission intensity $\int_i e_i di / \int_i q_i di$. The evolution of the aggregate emission intensity demonstrates that the outlined mechanism can explain most of the reduction present in the data.

Table 5: Validation model

Regression	*Firm Characteristics*				
	$I^{<2012}$		|	$I^{>2012}$	
	Data	Model	|	Data	Model
value added	0.038	0.051	|	0.054	0.062
	(0.011)		|	(0.011)	
Emission Intensity	0.078	0.10	|	0.51	0.12
	(0.009)		|	(0.011)	
Regression	*Price Impact*				
Interaction effect	0.002	0.037			
	(0.001)				

Comparison regression results of the data and model. The upper panel resumes the data results from specification (1) and (2) of Table 2 where the threshold $\lambda = 20\%$ and the corresponding regression results from a simulated dataset generated by the model. In the lower panel, the results for specification (1) of Table 3 are summarized, along with their counterparts from the model.

tion of the model estimates. Although the model's point estimates deviate, they remain comfortably within the 95% confidence interval derived from the data estimates for the firm characteristics. This alignment reinforces confidence in the reliability of the model.

5.2 Aggregate Implications

I first start by examining the aggregate implications of the introduction of the carbon policy. The taxation on carbon emissions can be seen as a wedge between the input factors and the outcome. An increase in this wedge will undoubtedly increase the aggregate price index and decrease the welfare. It is up to the government to determine how much of the price increase they are willing to accept in order to reduce aggregate emissions.

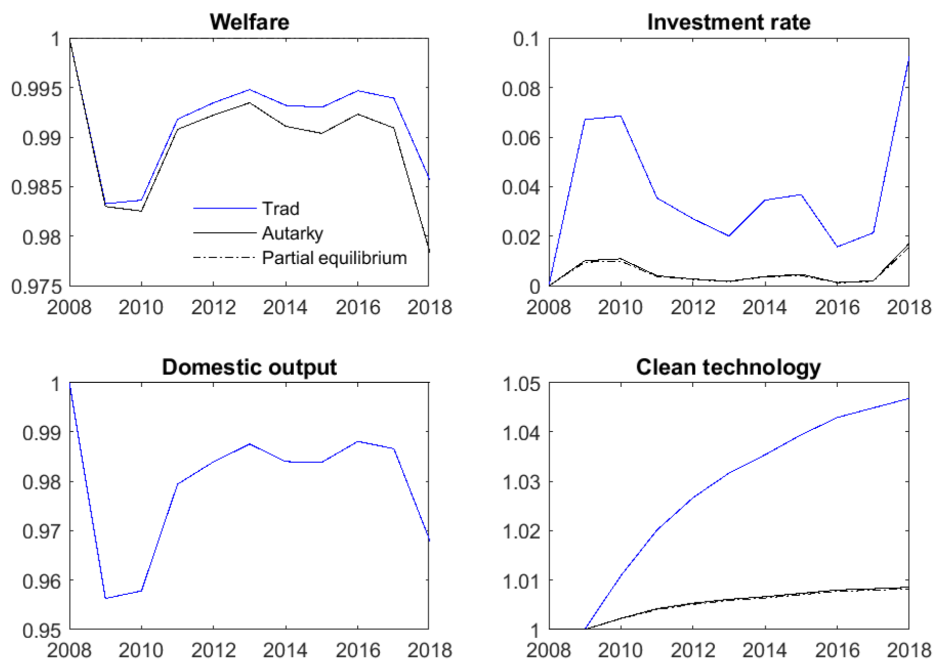

Figure 6: Aggregate outcomes

Aggregate Implications of the evolution of the carbon price relative to the level of 2008. For the outcomes (i) Welfare, (ii) the investment rate, (iii) domestic output and (iv) the level of clean technology. The are three versions of the model: trade (benchmark), autarky and the partial equilibrium model where there is neither trade nor any general equilibrium effect

The upper left panel of figure Figure 6 shows the evolution of the domestic output (i.e. the inverse of the aggregate price relative to the domestic wage) for the various scenarios relative to the situation in 2008. When the price of the carbon certificates increases, firms produce less, causing a welfare loss. As there is no general equilibrium present in the partial equilibrium model, the aggregate price index is not bound to change. The welfare loss is greater in the economy where firms are in autarky as there cannot be a substitution to imported goods. There seems to be little difference between the investment rate of the general equilibrium model relative to partial in the investment rate while. In contrast, the trade channel increases the downwards pressure on the aggregate price. This encourages firms to invest even more (panel ii) to overcome this hurdle.

5.3 Firm Inequality

The investment decision has major implications on different margins. First, on the clean technology margin, the dispersion between firms will become smaller as the most polluting firms will invest more often. Consequently, the standard deviation of clean technology will converge. Second, in contrast to the clean technology margin, the dispersion along the size margin - measured as either employment, output or profits (i.e. l, q, π) - will increase. Since $\partial l(z,s)/\partial s > 0 \mid \zeta > 0$, an investment in s will also increase the size of the firm, while firms that do not invest will stay on the same level. This will increase the standard deviation of the measure of size. Appendix A gives an theoretical overview of how the second moment is destined to change within the framework of this model. However, only the firms with a certain level of productivity will invest as the margin gain from the investment out-weights the cost. As the larger firms are getting more clean, they are also able to drive their marginal cost down and thus increase their market share even more. This can even have long-lasting, structural, consequences on the firm-size distribution through the potential exit from firms deciding to move abroad.[24]

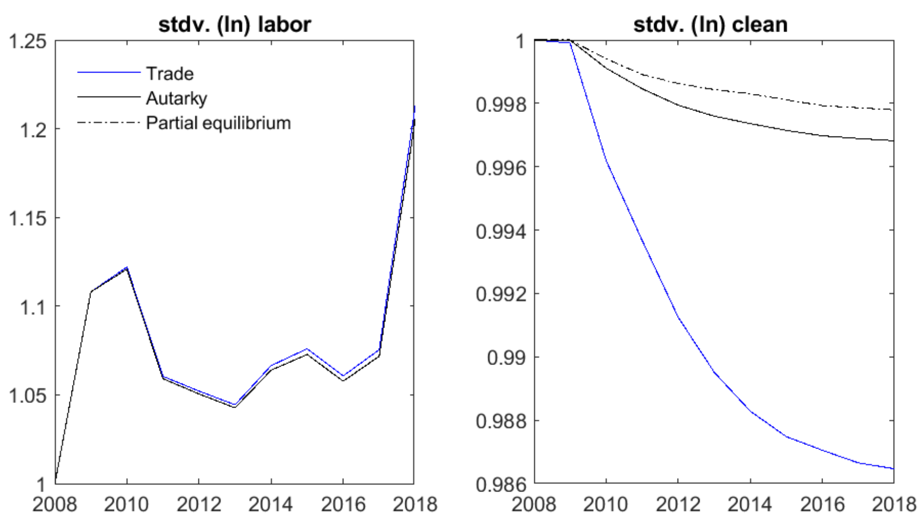

Figure 7: Evolution distribution

Evolution of the standard deviation of the logarithm of labor (left panel) and clean technology (right panel) for the 3 different models.

Figure 7 shows the evolution of standard deviation of clean technology and output as the measure of size. As intended, the standard deviation of output is increasing while the standard deviation of clean technology is slightly decreasing. These trends are more pronounced in the benchmark model with a trade margin, where investment decisions play a more prominent role. The evolution of output appears to be primarily influenced by the taxation and not so much by the investment decisions as it is relatively stable across the 3 types of models. Additionally, this mechanism would contribute to a rising covariance of clean

[24]The data also reveals a decrease in inequality on the emission intensity margin and an increase in inequality related to size. It's important to note that the decrease in the standard deviation of emission intensity may also be influenced by size, particularly through price pass-through. This can be seen in Appendix E

technology and size. The data reveals that the correlation between employment and emission intensity is increasing from -0.28 to -0.42.

To better understand how much of increasingly greener economy is driven by an aggregate reallocation of resources towards the large cleaner firms , I apply a shift-share analysis and decompose the changes in the aggregate level of clean technology S in to a between and within firm component $\Delta S = \int_i \Delta q_i \bar{s}_i + \int_i \bar{q}_i \Delta s_i$, where $\Delta q_i$and Δs_i denotes the market share in terms of output q and clean technology respectively. The prior component captures the reallocation towards the cleaner firms, The latter component captures the average increase in clean technology for the idiosyncratic firms.

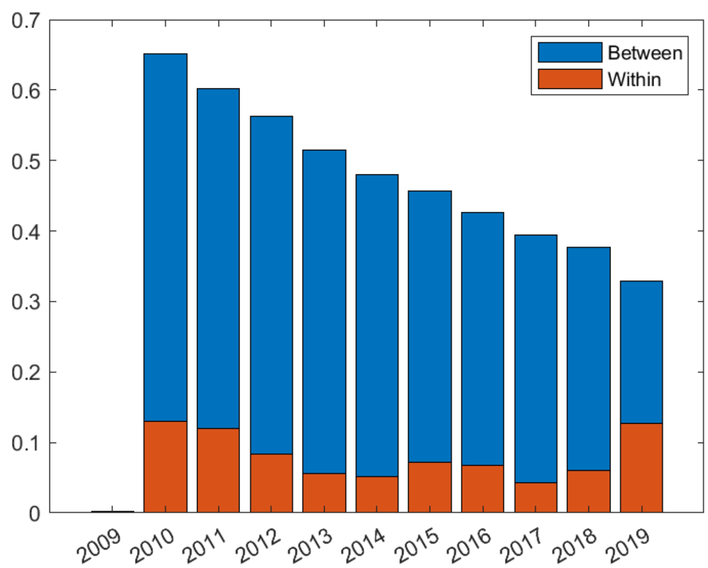

Figure 8: Clean Technology decomposition

Olley-Pakes decomposition of the yearly growth in clean technology for the period from 2008 to 2018. The total column for each year shows the percentage change in the level of clean technology. The bar can be decomposed in a within component (red) that shows what is driven by the individual firms and the between component (blue) that indicates the reallocation of resources from polluting firms to cleaner firms.

The results from Figure 8 indicate an annual improvement of approximately 0.5% in the overall cleanliness of the economy. However, this improvement primarily stems from a resource reallocation among firms, with cleaner firms facing fewer challenges in adapting to the carbon price increase. It is evident that the growth in aggregate clean technology is more pronounced in the initial years, gradually diminishing over time. This suggests that the collective, readily achievable improvements - where polluting firms significantly reduce production and their resources are redirected towards greener alternatives - have occurred, and now it's the responsibility of individual firms to adopt greener practices. As time progresses, the within-component becomes increasingly influential, reflecting the pivotal role of investment decisions in shaping the trajectory of aggregate clean technology.

6. Robustness and Extensions

TBC

6.1 Robustness

6.1.1 Heterogeneous subsidy κ

I start by introducing heterogeneous fixed cost subsidies, denoted as κ. These subsidies are based on the initial conditions of each firm prior to the implementation of the taxation scheme. So far, the allocation of κ was constant across firms. However, the positive correlation between the size of freely allocated certificates an output in the data suggests a strong relationship between productivity and emission certificates. I therefore adjust the allocation of fixed cost subsidies to each firm according to their level of productivity.

$$\kappa \equiv \kappa(z) = \frac{z\mu_h}{\int_z z\mu_h(z)dz} \int_z \kappa(z)\mu_h(z)dz \tag{18}$$

...

6.1.2 Differences in comparative advantage countries

Next, I So far the model assumes that both the home country and the foreign country produce with similar comparative advantages (i.e. $W_h = W_f$). This experiment emphasizes the often assumed to be advanced position of the European Union in the global world such that $W^h > W_f$. I reapply the model before for two different states in the world. the first considers the home country to have higher standards of living, $W_h = 1.1W_f$. The second state considers the home country to have lower wages $W_h = W_f/1.1$.

...

6.1.3 Endogenous entry and exit

The model thus far therefore opted to stay away from the extensive margin, as entry and exit are of second order of magnitude in the dynamics of this emission intensive sector, with an exit rate of only 3% and entry rate of only 1%. However, the implementation of the policy might severally hamper not only the intensive margin, but also fluctuations on the extensive margin.

I consider entry following Clementi and Palazzo (2016), where the share of entrants depends on the market clearing condition.

...

6.1.4 Endogenous evolution of carbon price ζ_t

The model considers the price of carbon as exogenously given. All other parameters are build around that. This way we can see how the However, this does not stroke with reality where governments determine the number of certificates and leave it up to the demand of by firms to set the price.

6.1.5 ...

6.2 Extensions

6.2.1 Multi-national firms and FDI

The model is characterized by each firm active either abroad or producing a unique good. In practice however, firms are more often active in different regions.

I consider horizontal FDI following **HELPMAN MELITZ AND YEAPLE 2004** where a constant mass of firms can choose to pay a fixed costs each period and open a plant into a different country. There are still 2 countries, and firms operate from their home country. The can decide either (i) not to produce at all, (ii) pay a fixed cost f_d and produce solely domestically and export abroad or (iii) open a second plant abroad where $f_{fdi} > f_d$.

This yields 2 major consequences. First, the domestic market clearing now is not only a function of domestic firms, but also firms abroad that opt for fdi. Second, this entails that now foreign firms will also invest in clean technology for their foreign plant. One major expectation is that the first firms to exit will be foreign multinationals as they have to pay the higher fixed cost.

...

6.2.2 Directed Technological change

In the benchmark model, the evolution of the stock of clean technology is exogenously determined and follows the evolution of productivity γ. In this section, I build upon Acemoglu et al. (2016) and consider a trade-off where researchers either have to produce a normal technology γ_t^z or can focus to produce γ_t^s. The parameter γ_t^z denotes the (upwards) evolution of productivity of the firms, in a given year while γ_t^s denotes the (upwards) evolution of the quality of the investment good. The quality of the investment good is 100% passed through the in the price, reflecting a perfect downwards evolution of the price of the investment good.

The researchers produce the evolution of clean technology $\dot{\gamma}_t^s$ using the demand for the investment good as their only input. The yearly demand for the good is given by the cost of the investment multiplied by the share of firms that invest in clean technology in that year $K_t = \int_\lambda k_\omega \omega_t(\lambda)\mu_t(\lambda)d\lambda$.

The production function for $\dot{\gamma}_t^s$ follows

$$\dot{\gamma}_t^s = \phi(\gamma_t^s)^\iota K_t \tag{19}$$

...

6.3 Alternative policies

6.3.1 Carbon border Adjustment Mechanism (CBAM)

6.3.2 Paris agreement

6.3.3 Investment subsidies

7. Conclusion

This study presents a comprehensive examination of carbon taxation on the firms decisions to investment in clean technology and its influence on aggregate technical change. The paper finds that more productive and polluting firms demonstrate a greater inclination to invest in clean technology when anticipating a high carbon price. This highlights the effectiveness of carbon taxation as a tool for reducing climate emissions. Albeit the policy yields substantial heterogeneous effects as only large firms are capable to invest in clean technology, the shift in aggregate clean technology is mostly driven by a large firms becoming greener an capturing a increased market share, while smaller firms are left behind. This research cannot differentiate between changes in input composition and changes in a firm's capacity to produce cleaner goods in their investment decision. Subsequent research could distinguish between the two to ascertain whether it represents the true capacity enhancement or merely a shift towards cleaner inputs.

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A. Analytical Results

B. Section 2: Investment decision

B.1 Inequality in Clean technology

In this section, I formally demonstrate that the firm decisions - investment and relocation - affect the first two moments of the distribution of clean technology. I assume that the distribution of clean technology is log-normal.On average the logarithm of clean technology will become higher and the variance will become smaller. To simplify notation I deviate from the notation used throughout the text and consider s to be the logarithm of clean technology such that $s \sim N(\bar{s}, \sigma_s)$.

B.1.1 First moment:

Assume that all firms $i \in N$ are endowed with a level of clean technology s_i. The mean level of clean technology can be denoted as

$$\bar{s} = \frac{1}{N}\sum_{i=1}^{N} s_i \tag{B.1}$$

Invest: There is a firm $j \in N$ with a low level of clean technology $s_j < s_i$ for all i, that finds it financially beneficial to invest in clean technology such that $s'_j = s_j + \delta_j$. All other firms $i \neq j \in N$ decide not to invest and keep their levels of s_i. The new mean of clean technology $\bar{s}'$ is consequently higher than the previous mean $\bar{s}$:

$$\bar{s}' = \frac{1}{N}\left(s'_j + \sum_{i \neq j}^{N-1} s_i\right) = \frac{1}{N}\left(\delta_j + \sum_{i=1}^{N} s_i\right) = \bar{s} + \frac{\delta_j}{N} > \bar{s} \tag{B.2}$$

Since $\delta_j/N > 0$, the new average level of clean technology will be higher than before.

Exit: If firm $j \in N$ finds in more beneficial to exit the market. To simplify notation I define $\varepsilon = \bar{s} - s_j$ as the distance to the original average. Then the average level of clean technology can be rewritten as

$$\bar{s}' = \frac{1}{N-1}\sum_{i \neq j}^{N-1} s_i = \frac{1}{N-1}\left(\sum_{i}^{N}(s_i) - s_j\right) = \frac{1}{N-1}\left(N\bar{s} - \bar{s} + \varepsilon\right) = \bar{s} + \frac{\varepsilon}{N-1} > \bar{s} \tag{B.3}$$

For as long as $\varepsilon > 0$ or stated differently, the level of clean technology j is below the mean $s_j < \bar{s}$, exiting the market would result in a higher mean value of clean technology.

Consequently, both firm decision lead for the most polluting firms lead to an increased average level of clean technology.

B.1.2 Second moment:

Similar to the case for the first moment, I also examine how the two decisions separately affect the variance of clean technology. As both decisions are additive, it is conclusive to argue that the variance of clean technology should decrease.

The original variance of clean technology can be written as

$$var(s) = \frac{1}{N}\sum_{i}^{N}(s_i - \bar{s})^2 \tag{B.4}$$

Invest: I first examine the case where firm $j \in N$ with the lowest level of clean technology $s_j < s_i \forall i$ decides to invest to $s'_j > s_j$. The new variance of clean technology $Var(s')$ is given by

$$var(s') = \frac{1}{N}\left[(s'_j - \bar{s}')^2 + \sum_{i \neq j}^{N-1}(s_i - \bar{s}')^2\right] \tag{B.5}$$

Plugging in the original mean and the distorting factor:

$$var(s') = \frac{1}{N}\left[\left(s_j + \delta_j - \bar{s} - \frac{\delta_j}{N}\right)^2 + \sum_{i \neq j}^{N-1}\left(s_i - \bar{s} - \frac{\delta_j}{N}\right)^2\right] \tag{B.6}$$

Decomposing he first term

$$\frac{1}{N}\left((s_j - \bar{s}) + \frac{(N-1)\delta_j}{N}\right)^2 = \frac{1}{N}(s_j - \bar{s})^2 + \frac{1}{N}\left[2(s_j - \bar{s})\frac{(N-1)\delta_j}{N} + \frac{(N-1)^2\delta_j^2}{N^2}\right] \tag{B.7}$$

The second term

$$\frac{1}{N}\left[\sum_{i \neq j}^{N-1}\left(s_i - \bar{s} - \frac{\delta_j}{N}\right)^2\right] = \frac{1}{N}\left[\sum_{i \neq j}^{N-1}(s_i - \bar{s})^2\right] + \frac{1}{N}\left[\sum_{i \neq j}^{N-1}2(s_i - \bar{s})\left(\frac{\delta_j}{N}\right)\right] + \frac{(N-1)\delta_j^2}{N^3} \tag{B.8}$$

Combining both terms, we get

$$var(s') = \frac{1}{N}\left[\sum_{i \neq j}^{N-1}(s_i - \bar{s})^2 + (s_j - \bar{s})^2\right] + \theta = var(s) + \theta \tag{B.9}$$

Where θ constitutes the rest term. It suffices for the rest term θ to be negative

$$\begin{aligned}
\theta &= \frac{1}{N}\left[\sum_{i \neq j}^{N-1}2(s_i - \bar{s})\left(\frac{\delta_j}{N}\right)\right] + \frac{(N-1)\delta_j^2}{N^3} + \frac{1}{N}\left[2(s_j - \bar{s})\frac{(N-1)\delta_j}{N} + \frac{(N-1)^2\delta_j^2}{N^2}\right] \\
\theta &= \frac{1}{N}\frac{2\delta_j}{N}\left[\sum_{i \neq j}^{N-1}(s_i - \bar{s})\right] + \frac{1}{N}\frac{2\delta_j}{N}(N-1)(s_j - \bar{s}) + \frac{(N-1)^2\delta_j^2}{N^3} + \frac{(N-1)\delta_j^2}{N^3} \\
\theta &= \frac{2\delta_j}{N^2}\left[\sum_{i \neq j}^{N-1}(s_i - \bar{s})\right] + \frac{2\delta_j}{N^2}(N-1)(s_j - \bar{s}) + \frac{2\delta_j}{N^2}[(s_j - \bar{s}) - (s_j - \bar{s})] + \frac{(N-1)\delta_j^2[(N-1)+1]}{N^3} \\
\theta &= \frac{2\delta_j}{N^2}(N-2)(s_j - \bar{s}) + \frac{(N-1)\delta_j^2}{N^2}
\end{aligned} \tag{B.10}$$

Consequently, θ is negative if the difference between s_j ans $\bar{s}$ is sufficiently large

Exit: The second case is the case where firm $j \in N$ with the lowest level of clean technology s_j decides to leave. We start by implementing the average level of clean technology in the new variance:

$$var(s') = \frac{1}{N-1}\sum_{i\neq j}^{N-1}(s_i - \bar{s}')^2 = \frac{1}{N-1}\sum_{i\neq j}^{N-1}\left(s_i - \bar{s} - \frac{\varepsilon}{N-1}\right)^2 \tag{B.11}$$

Decompose the square of a sum, and add $(s_j - \bar{s})^2$

$$var(s') = \frac{1}{N-1}\left[\left(\sum_{i\neq j}^{N-1}(s_i-\bar{s})^2 + 2(s_i-\bar{s})\frac{\varepsilon}{N-1} + \left(\frac{\varepsilon}{N-1}\right)^2\right) + (s_j-\bar{s})^2 - (s_j-\bar{s})^2\right] \tag{B.12}$$

Which includes the original variance $var(s)$ and and some rest values which we now denote as γ

$$var(s') = \frac{N}{N-1}var(s) + \gamma \tag{B.13}$$

Where the rest value $\gamma > var(s)$ for the variance to decrease over time

$$\begin{aligned}
\gamma &= \frac{1}{N-1}\left[\left(\sum_{i\neq j}^{N-1}2(s_i-\bar{s})\frac{\varepsilon}{N-1}\right) + \frac{\varepsilon^2}{N-1} - (-\varepsilon)^2\right] \\
\gamma &= \frac{1}{N-1}\left[\left(\sum_{i\neq j}^{N-1}-2(s_i-\bar{s})\frac{\varepsilon}{N-1}\right) + \frac{\varepsilon^2}{N-1} - (\varepsilon)^2\right] \\
\gamma &= \frac{1}{N-1}\left[\frac{-2\varepsilon}{N-1}\left((s_j-\bar{s}) - (s_j-\bar{s}) + \sum_{i\neq j}^{N-1}(s_i-\bar{s})\right) + \frac{\varepsilon^2}{N-1} - (\varepsilon)^2\frac{N-1}{N-1}\right] \\
\gamma &= \frac{1}{N-1}\left[\frac{-2\varepsilon}{N-1}\varepsilon + \frac{\varepsilon^2(2-N)}{N-1}\right] \\
\gamma &= \frac{\varepsilon^2}{N-1}\frac{-N}{N-1} = \frac{-\varepsilon^2 N}{(N-1)^2}
\end{aligned} \tag{B.14}$$

Such that $var(s') = \frac{N}{N-1}[var(s) - \varepsilon^2/(N-1)]$ Recall that $\varepsilon = s_j - \bar{s}$. As long as the gap ε between firm j and the average is larger than the drop of loosing one firm, the variance will decrease.

B.2 Inequality in output

The evolution of output requires a more economically structural approach. First, the taxation ζ directly affects the output, and not indirectly as was the case for the moments of clean technology. It is therefore essential to distinguish between the affect of the taxation as the implications of the two endogenous decisions on the two first moment of output. Additionally, to know how output has affected by the variables, it is essential to put some structure on either the production or the demand function that the firm faces.

As an example let's go to the case embodied within the framework of the structural model. For simplicity, and as discussed in Section 2, I abstract away from general equilibrium effects. Here, each firm faces the same downwards sloping demand $q_i = p_i^{-\eta}$ and the idiosyncratic prices are a markup over marginal cost $p_i = \mu(1+\zeta/exp(s_i))/exp(z_i)$. Here, akin to the previous section I consider s to be the logarithm of clean technology to simplify notation. Consequently, the log of output can be denoted as

$$\log(q_i) = \eta\left[-log(\mu) - log(1+\zeta/exp(s_i)) + z_i\right] \tag{B.15}$$

Simplify using a common Logarithmic Approximation of $log(1+\zeta/exp(s_i))$, assuming s_i is sufficiently small:

$$\log\left(1+\frac{\zeta}{exp(s_i)}\right) = log(\zeta) - s_i \tag{B.16}$$

Plugging this term in to the logarithm of the demand function:

$$\log(q) = \eta\left[-log(\mu) - log(\zeta) + s_i + z_i\right] \tag{B.17}$$

B.2.1 First Moment:

Firms differentiate solely in their level of clean technology s_i and their level of productivity z_i. The original average of output can be written as:

$$\overline{log(q)} = \frac{1}{N}\sum_i^N log(q_i) = \frac{1}{N}\sum_i^N \eta\left[-log(\mu) - log(\zeta) + s_i + z_i\right] = -\eta log(\mu\zeta) + \eta\bar{s} + \eta\bar{z} \tag{B.18}$$

where $\bar{z} = 1/N\sum^N z_i$ and $\bar{s} = 1/N\sum^N s_i$

Change in government policy ζ Now, assume that ζ increases. If there is no endogenous reaction to an increase in ζ. All firms will get hit, and the average output reduces hence the negative outcome of the first derivative.

$$\frac{\partial\overline{log(q)}}{\partial\zeta} = \frac{-\eta}{\zeta} < 0 \tag{B.19}$$

Invest Assume there are $i \in N$ firms, and ζ is sufficiently small such that only firm $j \in N$ with $z_j = \max_i\{z_i\}$ and $s_j = \min_i\{s_i\}$ finds it profitable enough to invest in clean technology. The new levels of clean technology after the investment will be $\bar{s}' = \bar{s} + \frac{\delta_j}{N}$

$$\overline{log(q')} = -\eta log(\mu\zeta) + \eta\bar{s}' + \eta\bar{z} = -\eta log(\mu\zeta) + \eta\bar{s} + \frac{\eta\delta_j}{N} + \eta\bar{z} = \overline{log(q')} + \frac{\eta\delta_j}{N} \tag{B.20}$$

Which is positive as long as $\delta_j > 0$.

Exit As documented in Section 2, only large, heavily polluting firms find it beneficial to relocate since they are the only ones for which this is profitable. Assume there are $i \in N$ firms, and ζ is sufficiently small such that only firm $j \in N$ with $z_j = \max_i\{z_i\}$ and $s_j = \min_i\{s_i\}$ finds it profitable enough to exit the home economy. The new average level of clean technology $\bar{s'}$ will experience an increase with $\bar{s'} = \bar{s} + (\bar{s} - s_j)/(N-1)$. This increase for the new average logarithm of output is positive as long as $\varepsilon_j = (\bar{s} - s_j) > 0$.

I first focus on the new variance of productivity. The mean $\bar{z}'$ can be reformulated to $\bar{z}' = \bar{z} + \tau/(N-1)$ with $\tau = \bar{z} - z_j$. The second term is negative, such that the new average level of productivity is lower as well.

$$\overline{log(q')} = -\eta log(\mu\zeta) + \eta\bar{s} + \frac{\eta\varepsilon_j}{N-1} + \eta\bar{z} + \frac{\eta\tau_j}{N-1} = \overline{log(q')} + \frac{\eta[\varepsilon_j + \tau_j]}{N-1} \tag{B.21}$$

B.2.2 Second Moment:

The variance of the original output is a function of both state variables s and z and the covariance term of the two.

$$\begin{aligned} var(log(q)) &= \frac{1}{N}\sum_i^N (log(q_i) - \overline{log(q)})^2 \\ &= \frac{\eta^2}{N}\sum_i^N (s_i + z_i - \bar{s} - \bar{z})^2 \\ &= \frac{\eta^2}{N}\sum_i^N [(s_i - \bar{s})^2 + 2(s_i - \bar{s})(z_i - \bar{z}) + (z_i - \bar{z})^2] \\ &= \eta^2[var(s) + 2cov(s,z) + var(z)] \end{aligned} \tag{B.22}$$

Invest The variance of the logarithm of output consists out of 3 components. $var(s)$, $cov(z,s)$ and $var(z)$. As investment is orthogonal to the productivity level of the firm, $var(z') = var(z)$. Additionally, from the evolution of the second moment of clean technology, we already established that $var(s') > var(s)$

$$\begin{aligned} cov(s',z') &= \frac{1}{N}\left[(s'_j - \bar{s}')(z_j - \bar{z}) + \sum_{i\neq j}^{N-1}(s_i - \bar{s}')(z_i - \bar{z})\right] \\ &= \frac{1}{N}\left[\left(s_j + \delta_j - \bar{s} - \frac{\delta_j}{N}\right)(z_j - \bar{z}) + \sum_{i\neq j}^{N-1}\left(s_i - \bar{s} - \frac{\delta_j}{N}\right)(z_i - \bar{z})\right] \end{aligned} \tag{B.23}$$

Reordering the terms, we get:

$$cov(s',z') = \frac{1}{N}\left[(s_j - \bar{s})(z_j - \bar{z}) + \left(\delta_j - \frac{\delta_j}{N}\right)(z_j - \bar{z}) + \sum_{i\neq j}^{N-1}(s_i - \bar{s})(z_i - \bar{z}) - \frac{\delta_j}{N}\sum_{i\neq j}^{N-1}(z_i - \bar{z})\right] \tag{B.24}$$

There exist three main components in this equation. The first equates to the covariance prior to the investment, while the second equates to 0. the third can be seen as the rest term $\delta_j(z_j - \bar{z})$.

$$\begin{aligned} (s_j - \bar{s})(z_j - \bar{z}) + \sum_{i\neq j}^{N-1}(s_i - \bar{s})(z_i - \bar{z}) &= \sum_i^N (s_i - \bar{s})(z_i - \bar{z}) = cov(s,z) \\ \frac{\delta_j}{N}(z_j - \bar{z}) + \frac{\delta_j}{N}\sum_{i\neq j}^N (z_i - \bar{z}) + &= \frac{\delta_j}{N}\sum_i^N (z_i - \bar{z}) = 0 \end{aligned} \tag{B.25}$$

Then this boils down to

$$cov(s',z') = cov(s,z) + \delta_j(z_j - \bar{z}) \tag{B.26}$$

As long as the more productive firms invest, $(z_j - \bar{z}) > 0$, the covariance between clean technology and productivity will increase over time as more firms invest.

Consequently, the evolution of the total variance of output depends on whether the covariance increases more than by which the variance of clean technology decreases.

$$\frac{\delta_j}{N}(z_j - \bar{z}) > \theta \tag{B.27}$$

Exit Finally, let's assume that firm $j \in N$ with $s_j = \min_i\{s_i\}$ and $z_j = \max_i\{z_i\}$ decides to exit the market instead. Then all three sub-components of log output shift. Not only the covariance with productivity shifts, but also the variance itself.

$$var(z') = \frac{1}{N-1}\sum_{i \neq j}^{N-1}(z'_i - \bar{z}')^2 \tag{B.28}$$

$$\begin{aligned}
var(z') &= \frac{1}{N-1}\left[(z_j - \bar{z})^2 - (z_j - \bar{z})^2 + \sum_{i \neq j}^{N-1}\left(z_i - \bar{z} - \frac{\tau}{N-1}\right)^2\right] \\
var(z') &= \frac{1}{N-1}\left[(z_j - \bar{z})^2 - (\tau)^2 + \sum_{i \neq j}^{N-1}(z_i - \bar{z})^2 - 2(z_i - \bar{z})\frac{\tau}{N-1} + \left(\frac{\tau}{N-1}\right)^2\right] \\
var(z') &= \frac{N}{N-1}var(z) + \frac{1}{N-1}\left[-(\tau)^2 + \sum_{i \neq j}^{N-1} -2(z_i - \bar{z})\frac{\tau}{N-1} + \left(\frac{\tau}{N-1}\right)^2\right] \\
var(z') &= \frac{N}{N-1}var(z) + \frac{1}{N-1}\left[-(\tau)^2 + \frac{-2\tau}{N-1}\left((z_j - \bar{z}) - (z_j - \bar{z}) + \sum_{i \neq j}^{N-1}(z_i - \bar{z})\right) + \frac{\tau^2}{N-1}\right] \\
var(z') &= \frac{N}{N-1}var(z) + \frac{1}{N-1}\left[-(\tau)^2 + \frac{-2\tau}{N-1}\tau + \frac{\tau^2}{N-1}\right] \\
var(z') &= \frac{N}{N-1}var(z) + \frac{\tau^2}{N-1}\left[\frac{-2}{N-1} + \frac{1}{N-1} - \frac{N-1}{N-1}\right] \\
var(z') &= \frac{N}{N-1}var(z) + \frac{\tau^2}{N-1}\frac{-N}{N-1} \\
var(z') &= \frac{N}{N-1}\left[var(z) - \frac{\tau^2}{N-1}\right]
\end{aligned} \tag{B.29}$$

As long as $\tau < 0$ and $N > 1$, the second term will be positive. Whether the variance of z increases.

The covariance term

$$
\begin{aligned}
cov(s',z') &= \frac{1}{N-1}\left[\sum_{i\neq j}^{N-1}(s_i-\bar{s}')(z_j-\bar{z}')\right]\\
cov(s',z') &= \frac{1}{N-1}\left[(s_j-\bar{s})(z_i-\bar{z})-(s_j-\bar{s})(z_j-\bar{z})+\sum_{i\neq j}^{N-1}\left(s_i-\bar{s}-\frac{\varepsilon}{N-1}\right)\left(z_i-\bar{z}-\frac{\tau}{N-1}\right)\right]\\
cov(s',z') &= \frac{1}{N-1}\left[(s_j-\bar{s})(z_i-\bar{z})-(s_j-\bar{s})(z_j-\bar{z})+\sum_{i\neq j}^{N-1}\left((s_i-\bar{s})(z_i-\bar{z})-\frac{\tau}{N-1}(s_i-\bar{s})-\frac{\varepsilon}{N-1}(z_i-\bar{z})+\frac{\tau\varepsilon}{(N-1)^2}\right)\right]\\
cov(s',z') &= \frac{1}{N-1}\left[Ncov(z,s)-(s_j-\bar{s})(z_j-\bar{z})+\frac{1}{N-1}\sum_{i\neq j}^{N-1}\left(-\tau(s_i-\bar{s})-\varepsilon(z_i-\bar{z})+\frac{\tau\varepsilon}{(N-1)}\right)\right]\\
cov(s',z') &= \frac{1}{N-1}\left[Ncov(z,s)-\frac{(N-1)\tau\varepsilon}{(N-1)}+\frac{1}{N-1}\sum_{i\neq j}^{N-1}(\tau(s_i-\bar{s}))-\frac{1}{N-1}\sum_{i\neq j}^{N-1}(\varepsilon(z_i-\bar{z}))+\frac{\tau\varepsilon}{(N-1)}\right]\\
cov(s',z') &= \frac{1}{N-1}\left[Ncov(z,s)-\frac{(N-2)\tau\varepsilon}{(N-1)}+\frac{\tau}{N-1}\left((s_j-\bar{s})-(s_j-\bar{s})+\sum_{i\neq j}^{N-1}(s_i-\bar{s})\right)-\frac{\varepsilon}{N-1}\left((z_j-\bar{z})-(z_j-\bar{z})+\sum_{i\neq j}^{N-1}(z_i-\bar{z})\right)\right]\\
cov(s',z') &= \frac{1}{N-1}\left[Ncov(z,s)-\frac{(N-2)\tau\varepsilon}{(N-1)}-\frac{\tau}{N-1}(\varepsilon)-\frac{\varepsilon}{N-1}\tau\right]\\
cov(s',z') &= \frac{1}{N-1}\left[Ncov(z,s)-\frac{N\varepsilon\tau}{N-1}\right]
\end{aligned}
\tag{B.30}
$$

Thus, whether the variance goes up after the firm exits depends on XXX and XXX and XXX.

B.3 General equilibrium effects

B.3.1 Market conduct - output market

The implications of market conduct on the investment decision are a priori uncertain. and depend on the excess profit Δv that firms expect to receive after their investment. Suppose all firms with a certain state variable of clean technology j receive profit $v(s_j,\Theta|\kappa,\zeta)$ conditional on the governmental policies, κ and ζ, where Θ represents the degree of competition present in the output market.

Increased investment from other firms i would increase their market share $v(s_i',\Theta|\kappa,\zeta)$, this would in turn reduce current value of the firm $v(s_j,\Theta|\kappa,\zeta)$ through the increase of Θ. This in turn would make it more worthwhile for the firm to invest as well as their market share gets reduced. However, it would also reduce future expected values as the new firm cannot increase their market share anymore. Consequently, the impact on $\Delta v(s_j,\Theta|\kappa,\zeta)$ is unclear. If $\partial\Delta v(s_j,\Theta|\kappa,\zeta)/\partial\Theta > 0$ the prevalence of firms investing would increase. In contrast the opposite sign of the derivative is equally as likely. Note that the inverse relationship that exists between productivity and innovation as discussed by Aghion et al. (2018) could potentially be present here as well. The presence of trade with firms from countries where there are no such factors is another potential distortion that firms face in their investment decision.

B.3.2 Market conduct - carbon certificates

One aspect not thoroughly addressed in this paper thus far is the potential endogeneity of the carbon price of certificates on the market conduct $\zeta(\Theta)$. in the empirical section of this paper I assume that firms are price-takers in the carbon market and control for increased conduct through price deflators. If firms exhibit above-average shifts in performance, this may indicate a heightened demand for carbon certificates. However, given that the quantity of certificates is capped, it inevitably leads to a rise in the price of emissions.

C. Section 4: Trade dynamics without endogenous decisions

To see how the aggregate variables would evolve if firms would not have the capability to endogenously adjust their level of clean technology, I consider two simple variations of the model laid out Section 4, where firms face CES demand and monopolistic competition.

C.1 Balanced growth with constant governmental policy ζ, κ

The evolution of output is given buy an exogenously determined constant growth rate homogeneous for all firms such that productivity $z_t = \gamma z_{t-1}$. As prices yield perfect pass-through, the evolution of price $p_t = p_{t-1}/\gamma$. As the growth rate is homogeneous across firms, the aggregate price index evolves accordingly, $P_t = P_{t-1}/\gamma$. Income remains constant across this exercise. This in turn signifies that aggregate demand evolves positively $Q_t = I_t/P_t = \gamma I_{t-1}/P_{t-1} = \gamma Q_{t-1}$. akin to the aggregation, as the technological progress is constant across firms, the distribution stays constant, which yields an increase of $q_t = \gamma q_{t-1}$.

Turning towards the emission output. idiosyncratic emissions are a function of the total output and the level of clean technology of the firm, $e_t = s_t q_t$. since firms cannot invest, thus not change the level of clean technology s_t, emissions would increase at a similar pace as aggregate output, $e_t \gamma e_{t-1}$.

C.2 Change in governmental policy $\Delta\zeta > 0$

In this exercise, I examine how the policy would affect aggregate variables, assuming away any long-term adjustments at the firm-level as well as the implications of κ by not allowing for adjustments through the trade channel. As firms cannot alter their decisions, the fixed cost subsidy κ has no effect on any of the aggregate variables as it cannot influence the decision to move abroad. The latter I will relax in the following section.

In order to facilitate a closed form solution, the analytical version of the model differs in a additional way - aside from the no trade and no endogenous decision assumption - where I assume that the marginal costs for each firm are captured by a change in marginal cost from $mc = W s_t \zeta$ instead of the nonlinear $mc = W(1 + s_t \zeta)$.[25]. This version of the model yields a 100% pass through of the carbon taxation: $\Delta p_t = \Delta\zeta$. The aggregate price index increases with a similar rate as ζ does not depend on i, and as a consequence demand has to reduce to keep income constant. In essence, this would boil to a linear constant decrease of aggregate emissions $\Delta e_t = s_t \Delta q_t$ for all firms through the constant reduction of q_t, thus not affecting the market share of each firm.

[25] Employing this simplifying assumption on the marginal cost of the firm $mc_t = W s_t \zeta$, would consider s_i as indifferent from a general type of productivity, thus simplifying the closed-form solution significantly. While aggregate variables would move the same way as with the more complicated marginal cost. This assumption overlook potential distributional effects of the taxation on.

D. Accompanying notes empirical analysis

D.1 Data gathering process

D.1.1 Emission data

The data gathering process starts with the gathering of the data on the European Transaction log data from 2005 to 2020. The preparation closely follows the methodology by JaraitÄ et al. (2016). Emission data is presented on the installation level. To match this with the financial data from ORBIS, I aggregate the data to the registration number unique to each company. During this consolidation, airline companies and entities having an account, but lacking an installation identifier with the EU EUTL are excluded. Such accounts are typically utilized solely for trading carbon certificates. In cases where a firm possesses multiple accounts but at least one of those accounts is linked to an installation that omits emissions, the emission certificates used will be aggregated up to the firm level. Consequently, if the firm sells or closes an installation, this will have a major impact on their emission usage.

After, I slightly adjust the matching procedure of Letout (2022) and match the data from EUTL database with the financial data or ORBIS. This allows me to look at financial data. The analysis is limited to the manufacturing sector as the firms operating in this sector are relatively comparable to each other.

D.1.2 Other datasources

D.2 Emission intensity and clean technology

In a setting with perfect competition, emission intensity would be a perfect indicator for clean technology as prices are set by demand of the homogenous good and do not depend on the firm characteristics. However in other settings the price pass through is not equal to zero, therefore changes in price might reflect changes in clean technology.

$$\tilde{s_{i,t}} = \frac{1}{s_{i,t} p_{i,t}} \tag{D.31}$$

Within the framework of our structural model with autarky, the price can be denoted as follows: , $p = \frac{\eta}{\eta-1} \frac{W(1+\zeta/s_{i,t})}{z}$

$$\begin{aligned}
\tilde{s_{i,t}} &= \frac{1}{s_{i,t} p_{i,t}} = \frac{1}{s_{i,t} \frac{\eta}{\eta-1} \frac{1+\zeta/s_{i,t}}{z_{i,t}}} \\
\tilde{s_{i,t}} &= \frac{\eta-1}{\eta} \frac{z_{i,t}}{s_{i,t}+\zeta} \\
\tilde{s_{i,t}} &= \frac{\eta-1}{\eta} \frac{z_{i,t}}{s_{i,t}+\zeta}
\end{aligned} \tag{D.32}$$

to see what happens in emission intensity when a change in clean technology occurs, I take the derivate w.r.t. clean technology. The expression is always positive. And as $\tilde{s_{i,t}}$ and $z_{i,t}$ are always positive as well, they are positively correlated. The magnitude of the correlation depends on the parameter ζ.

$$\begin{aligned}
\frac{\partial \tilde{s_{i,t}}}{\partial s_{i,t}} &= \frac{\frac{\eta-1}{\eta} z_{i,t}(1+\zeta s_{i,t}) - \zeta \frac{\eta-1}{\eta} s_{i,t} z_{i,t}}{(1+\zeta s_{i,t})^2} \\
&= \frac{\frac{\eta-1}{\eta} z_{i,t} + \frac{\eta-1}{\eta} z_{i,t} \zeta s_{i,t} - \zeta \frac{\eta-1}{\eta} s_{i,t} z_{i,t}}{(1+\zeta s_{i,t})^2} \\
0 &< \frac{\eta-1}{\eta} \frac{z_{i,t}}{(1+\zeta s_{i,t})^2} \qquad \forall\, s_{i,t} > 0
\end{aligned} \tag{D.33}$$

The second derivative w.r.t. clean technology equals

$$\begin{aligned}
\frac{\partial^2 \tilde{s_{i,t}}}{\partial^2 s_{i,t}} &= \frac{\eta-1}{\eta} \frac{z_{i,t} 2(1+\zeta s_{i,t})\zeta}{(1+\zeta s_{i,t})^4} \\
0 &> -\frac{\eta-1}{\eta} \frac{2 z_{i,t} \zeta}{(1+\zeta s_{i,t})^3}
\end{aligned} \tag{D.34}$$

The second derivative is negative as long as productivity and the price of emissions are positive. Suggesting that emission intensity is not linearly increasing in clean technology.

Productivity Changes in emission intensity are influenced not only by clean technology but also by productivity. An increase in productivity affects emission intensity, as indicated by the positive first derivative

$$\frac{\partial \tilde{s_{i,t}}}{\partial z_{i,t}} = \frac{\eta-1}{\eta} \frac{s_{i,t}}{1+\zeta s_{i,t}} > 0 \tag{D.35}$$

The second derivative is zero, suggesting a linear relationship between emissions and productivity. Consequently, a 20% increase in productivity would imply a 20% increase in emission intensity.

D.3 Validation investment indicator

The decision to invest in the empirical section is arbitrarily constructed and based on various explicit and implicit assumptions. In this section I will apply various robustness tests to validate the indicator used in the text. First I will tests, whether the functional form of the indicator matters and, if so, by how much. Second, to speak of investment firms have to truly buy something tangible, in other words, there have to be changes in capital at the same time. I will look at that. And finally I will look at the relation with other variables as well to see which other variables are moving similarly to my indicator to uncover whether there are other factors at play then just investment.

D.3.1 Functional forms

There are several assumptions that are important in constructing the investment indicator. First I will examine whether the investment threshold λ matters. Second I will dive deeper into the functional form, mainly into the transitory state and whether the choice matters also in likelihood of its occurrence and as a good indicator. Finally, I will also look at whether the choice of the parameters B and W that govern the length of the structural state matters.

To facilitate comparison with the baseline equation, the functional form of the equation used to measure investment in clean technology in the main text is repeated:

$$\omega_{i,t} = 1\underbrace{\{\tilde{s}_{i,t} \geq (1+\lambda)\tilde{s}_{i,t+1}\}}_{\text{Transitory state}}\underbrace{\left\{(1+\lambda)\frac{1}{B}\sum_{b=1}^{B=2}\tilde{s}_{i,t+b} \leq \frac{1}{W+1}\sum_{w=0}^{W=2}\tilde{s}_{i,t-w}\right\}}_{\text{structural state}} \tag{D.36}$$

Different values of threshold λ One of the things that is arbitrarily chosen is the threshold value that the reduction in emission intensity has to surpass in order to be called an investment. As already visible in **??**, there exists considerable differences between the occurrences of investment threshold. The likelihood of a firm making an investment decreases as the threshold value λ increases. There's a delicate balance: if the investment threshold λ is set too low, it might inadvertently capture fluctuations in demand or productivity, as highlighted in Appendix **??**. Conversely, if λ is set too high, it risks missing out on certain investments in clean technology altogether. Table Table D.1 presents the frequency of each investment occurrence. I find that a value of $\lambda = 20\%$ strikes a sweet spot, where it is limited by changes in value added through demand or productivity and still captures changes in emission output.

Different threshold for the Transitory state Throughout the analysis, I adopt a transitory state (1) where the future $\tilde{s}_{i,t+1}$ is structurally lower than the present period. Explanation (2) and (3) essentially share the same concept, wherein (3) requires the current $\tilde{s}_{i,t}$ to be significantly higher than the future average value of emission intensity and (2) the inverse. Conversely, (4) eliminates the shock entirely, leading to frequent "investment" occurrences which are almost annually, contradicting the typical lumpiness of investment decisions.

$$
\begin{aligned}
(1): &\quad \{\tilde{s}_{i,t} \geq (1+\lambda)\tilde{s}_{i,t+1}\} \\
(2): &\quad \left\{(1+\lambda)\tilde{s}_{i,t+1} \leq \frac{1}{W+1}\sum_{w=0}^{W=2}\tilde{s}_{i,t-w}\right\} \\
(3): &\quad \left\{(1+\lambda)\frac{1}{B}\sum_{b=1}^{B=2}\tilde{s}_{i,t+b} \leq \tilde{s}_{i,t}\right\} \\
(4): &\quad \text{No transitory state}
\end{aligned}
\tag{D.37}
$$

The frequency of each investment is reported in table Table D.1

Table D.1: Model results

	threshold value				|	Functional form			
	5%	10%	20%	30%	|	(1)	(2)	(3)	(4)
Invested (%)	0.061	0.775	0.900	0.226	|	6.677	0.713	0.237	
Not invested (%)	0.188	0.813	0.899	0.216	|	2.680	0.764	0.255	

This table displays the share of investment occurrence based on the functional form of the investment parameters. The share of investments monotonically increase in λ. As the threshold value gets more stringent, the share of investments reduces.

Different values timing values W and B The timing values W and B describe the length for which investment has to be structurally higher (lower) than before (after). Similar to the threshold value λ, the selection of the threshold length is also bound by a trade-off. Too long of a pre-and post-investment period reduces the period that I can actually measure whether the firm has invested in clean technology. Conversely, if the period is too brief, it risks capturing only a transient shock rather than a lasting structural shift in emission intensity. In the baseline model, I opt for a three-year period for W, which aligns perfectly with the initial phase of the ETS (2005-2007) when the market was still nascent and carbon certificate prices were undetermined. For B, a duration of two years is chosen, ensuring that the latest year for measuring investment decisions is 2018, thereby avoiding excessive restriction on the sample.

To test whether the selection of B and W drives the result, I plot the average emission intensity before and after the investment decision for all firms that have invested exactly once in Figure D.1. I pick a period of 4 years prior and 4 years after the investment decision at time=0, which is longer than B and W. The results seem to be structural, and do not shoot up as the restriction has been lifted, suggesting that the selection of the values is well chosen.

Divestment Another control I can do to check whether this indicator of investment is truly an indicator of investment. I reapply the baseline indicator above, but switch the inequality signs around, such that the investment indicator essentially becomes an indicator of divestment. I stick to the assumptions of

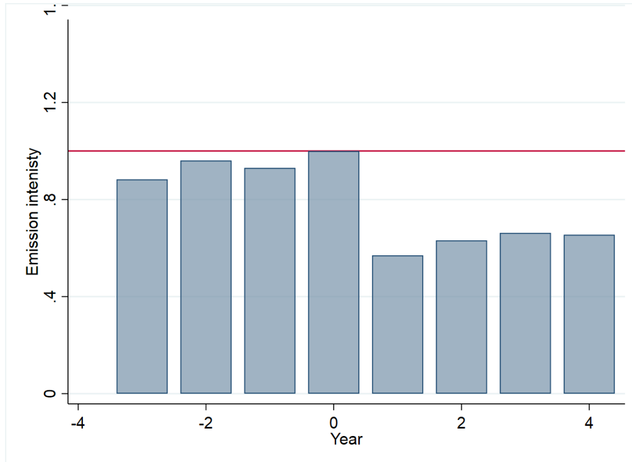


Figure D.1: Average emission intensity

$B = 2$, $W = 2$ and $\lambda = 20\%$, akin to the function form of the investment indicator. In other words, firms are considered to be divesting if they structurally increase their emission intensity by at least 20%. Examples of such a divestment could be the the acquisition of a new plant or the sale of a clean filter that would be too costly to maintain.

Divestment occur less than investments but still reasonably often, especially between 2012 and 2013. The year 2012 is off because of the fact that in 2013 the Transaction System progressed from phase II to phase III which introduced more stringent measures and included more sectors. This made that the some installations were now included that were prior exempt from the policy. On the firm level, this causes the emission output per firm to increase significantly.

D.3.2 Relation to Capital

In order to speak of an investment, it is not only sufficient to say that emission intensity got reduced substantially in a a given year, but also that firms have actually invest. To measure Investment, I use a very rudimentary form of *Fixed Tangible Assets*. The variable covers all assets with physical value, such as equipment and machinery, where it is much more likely for investment in clean technology to appear.

To construct the following figures, I omit all firms that do not invest or have invested more than once throughout their lifetime. This way I restrict the data to approximately 30% of the total data (as 60% of all firms never invest, and another 10% invests more than once throughout the span of the analysis). The year in which firms invest is set to zero, such that years prior to the investment decision are negative. Subsequently, the average is for each year is taken. The data is winsorized at the 2.5% level for the averages not to be deluded by outliers. Finally, I normalize the data such that the level of year 0 is equal to 1 and all other years are relative to year 0. As discussed before, it might be possible that when the functional form constraint of B and W is met, all values shoot back up to their earlier state. To test for this, I set the years in each graph to -4 and $+4$.

Figure D.2 - Figure D.4 show the average levels of emission intensity (left panel) and capital (right panel)

Figure D.2: All firms

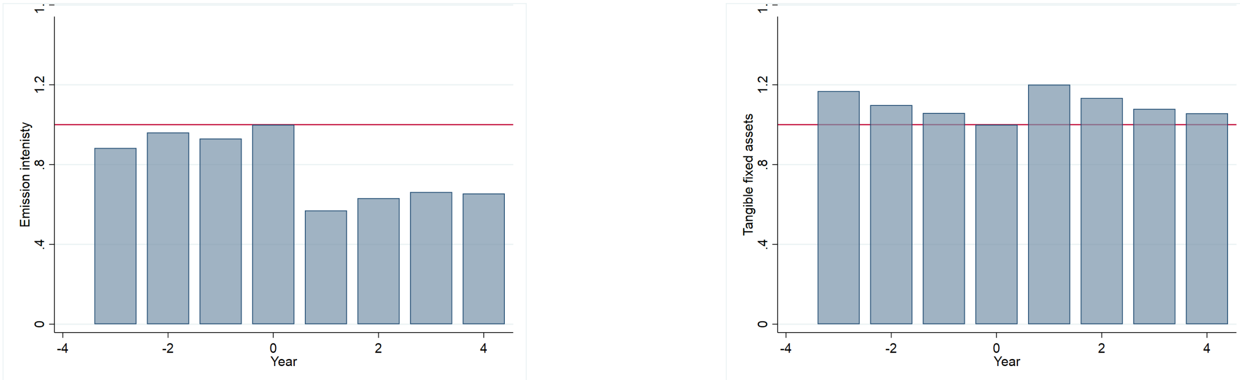
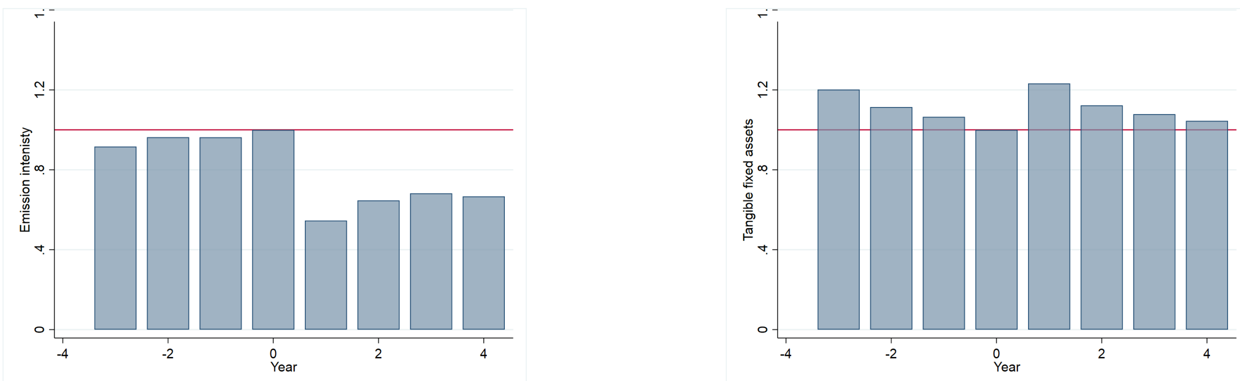
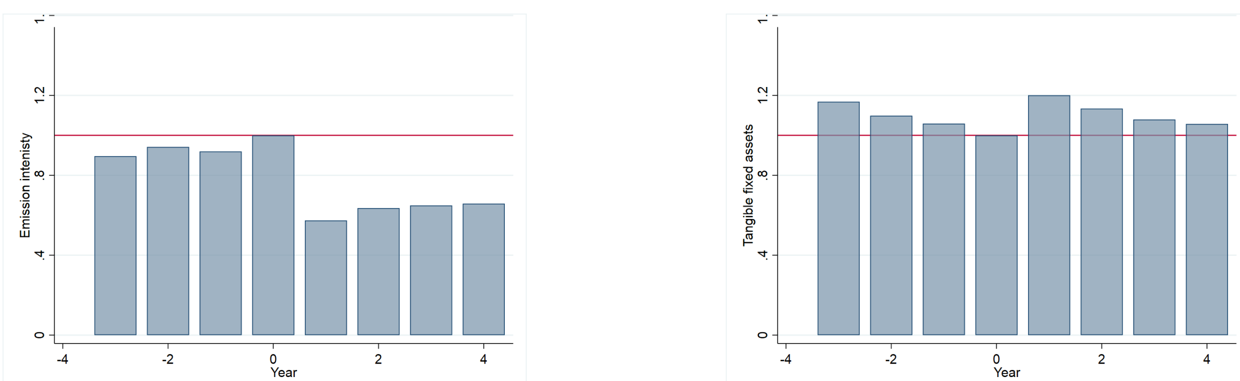


Figure D.3: Only Manufacturing



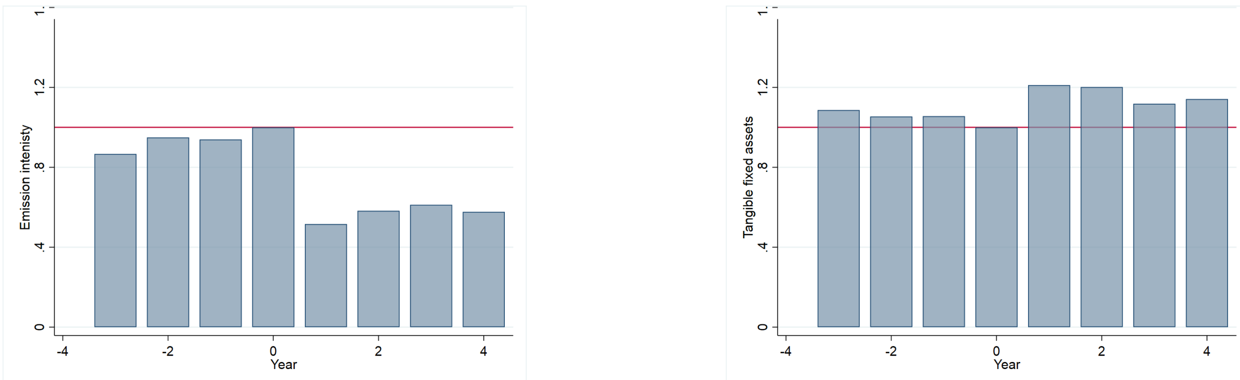
before and after the investment decision for all firms that have invested only once throughout their lifetime. In Figure D.2, the analysis reveals a significant shock in the firm's capital, that indicates investment, which demonstrates that the firm did indeed invest at the time of the shock. Additionally, one can also remark the yearly gradual decline in capital both post and prior to the shock, which I interpret as the depreciation.

Figure D.4: Only intensive margin



To examine potential heterogeneity among groups, I replicate this analysis for two subsets: firms exclusively active in the manufacturing sector and firms that remained active throughout the period without exiting or entering. The results stay consistent with the baseline figure and they don not seems to be subject to sample selection.

Figure D.5: Post 2010



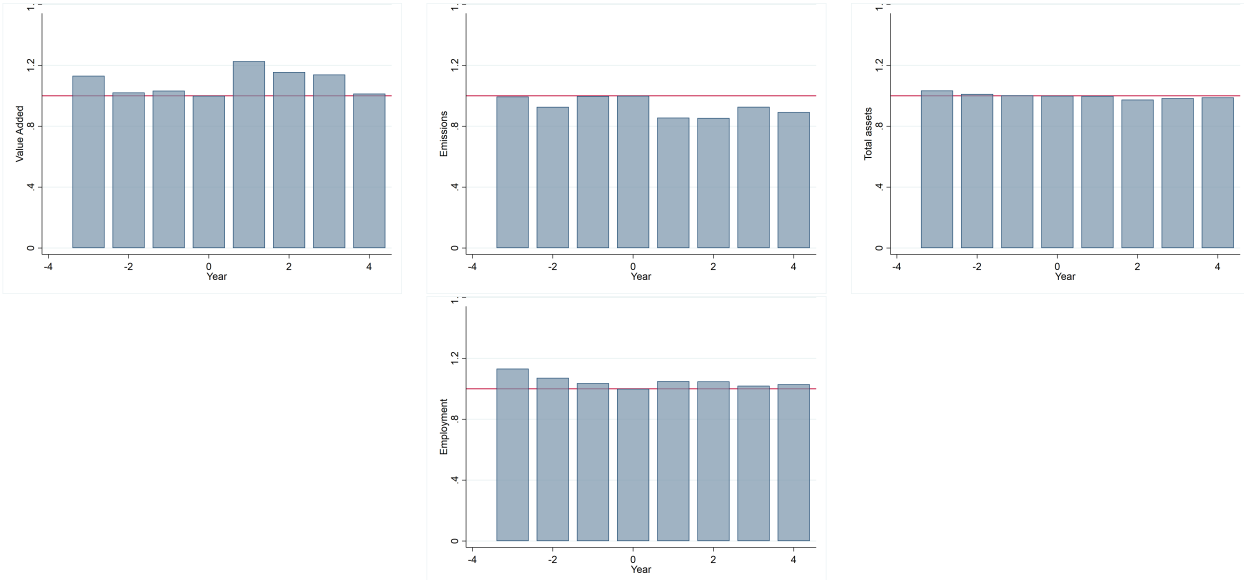
This scope of this analysis includes the financial crisis of 2007 - 2008 and its aftermath. The crisis has affected the value of many European firms substantially, especially those operating in manufacturing (XXX). Consequently, the indicator could partially be affected by substantial and structural changes in productivity of the good. To combat this problem, I reapply the analysis on the investment decision post 2010. Figure D.5 shows the average impact emission intensity and capital before and after the investment decision. The results stay highly consistent with the main results in the previous section, therefore conforming that the impact of the investment decision is not completely driven by changes due to the financial crisis.

Other variables I also compare the impact of the investment decision in clean technology on other variables. Figure D.6 shows the evolution of the average value added, emissions, total assets and employment before and after the investment decision.

The investment decision is associated with a reduction in value added for that specific year relative to all other years. This might be due to the fact that it is costly for firms to invest in clean technology. After the shock it is slightly higher, which in turn would reflect the fact that the investment not only made the firm cleaner, it might it more profitable as well. This could be either directly, through the fact that these firms now have to pay less on their emission output, or indirectly, as the new investment might not only be cleaner, but also more productive than the old machinery. Moreover, the investment does decrease average emissions per firms as can be seen in the upper right panel.

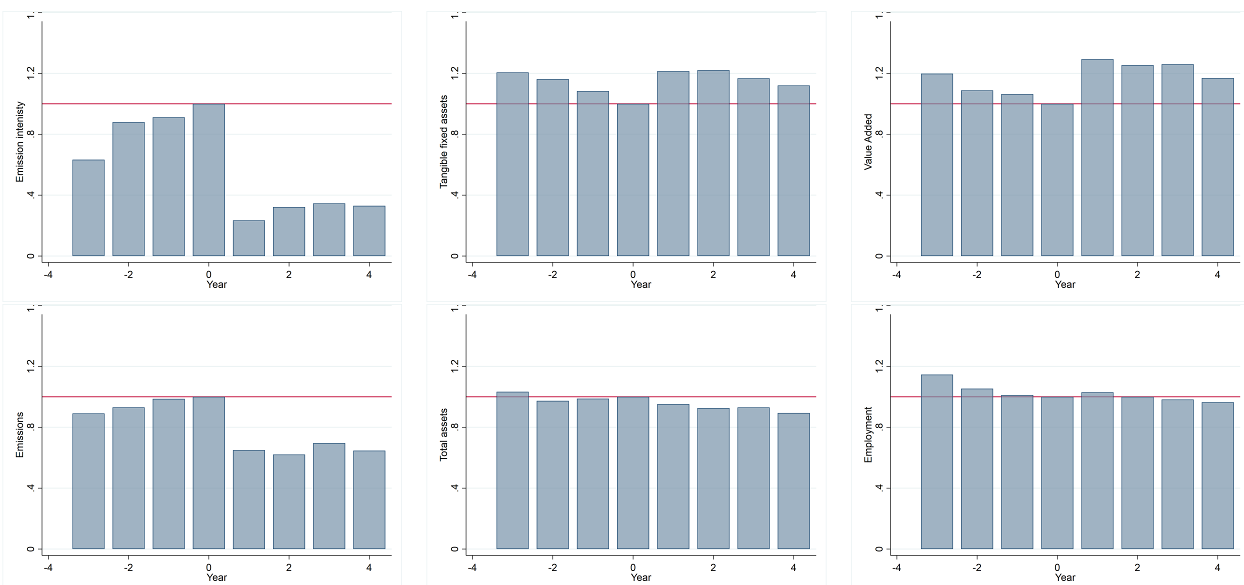
Finally, I consider the effects of the investment decision on other variables such as total assets and employment. Both figures seem to remain relatively over time. This suggests that the investment factor is not driven by other potential reasons.

Figure D.6: Other variables



Median the results above can be driven by outliers. The previous results already correct for it by removing all outliers above the 2.5 percentile. The approach here is by taking the median firm instead of the average. Figure D.7 shows the median results for all variables. As in the previous exercises, the results are depicted relative to year 0, which is the year the firms decide to invest.

Figure D.7: Other variables



D.4 Aggregate descriptives

D.4.1 Cross-country distribution

Table D.2 compares the investment rate across countries for 3 different thresholds of the investment indicator. Aside from the Netherlands, for which only 7 observations are available, firms in all countries decide to invest. This finding suggests that the decision to invest in clean technology is not specific to firms operating in any particular country, which might indicate a common factor such as the overarching EU ETS in encouraging such investments.

Table D.2: Cross-country comparison

country	observations	investment ($\lambda = 20\%$)	innovation	Added Value	Emission Intensity
LV	244	0	0	0	.065
IE	188	.4	.05	.001	.203
LU	164	.18	0	.001	.084
RO	1243	.43	.02	.003	.05
SI	1128	.32	.02	.003	.036
BG	1129	.47	.02	.003	.064
HU	1208	.5	.02	.005	.072
SK	1033	.46	.06	.005	.08
NL	1230	0	.04	.01	.041
PL	4181	.3	.03	.011	.089
CZ	2175	.54	.04	.013	.041
SE	2073	.36	.11	.014	.042
PT	3135	.45	.03	.018	.029
FI	822	.05	.07	.019	.02
AT	1220	.54	.13	.024	.016
IT	9239	.5	.03	.092	.015
GB	3996	.42	.09	.093	.008
ES	11193	.53	.04	.117	.016
BE	3986	.46	.12	.119	.01
FR	7234	.5	.16	.126	.012
DE	5642	.44	.09	.321	.008

Cross-country comparison of investment, innovation, Value added and aggregate Emission intensity across countries. For the latter two variables, the averages of 2005 to 2008 is taken, prior to phase 2 of EU ETS. I depict the share of the country in the total. I.E. 32% of all value added in EU ETS is produced in Germany prior. Investment and innovation document the share of firms engaging in either in throughout the period.

The heterogeneity observed in clean technology investment across countries may be attributed to differences in industrial policies related to emission control and sectoral composition. The prevalence of more emission intense firms in a certain country might bias the aggregate statistics. As illustrated in the preceding section, firms in certain sectors demonstrate notably higher investment levels compared to those in other sectors. This sectoral composition might also affect the industrial policies enacted by the national governments, making it challenging to draw definitive conclusions from this descriptive table. Despite these nuances, the overarching observation remains that firms in all countries exhibit a tendency to invest in clean technology.

D.4.2 Cross-sectoral distribution

There is substantial heterogeneity in the investment decisions across sectors. Table D.3 shows the investment rate per sector for the firms operating in the manufacturing sector (Nace rev. 2 2-digit >10 and < 33). The sectors are indicated by their Nace rev.2 2-digit code. Investments are significantly more common for firms operating in the following industries: 15 (Manufacture of leather and related products), 29 (Manufacture of motor vehicles, trailers and semi-trailers) and 19 (Manufacture of coke and refined petroleum products).

Table D.3: Cross-sectoral comparison

Nace 2 - digit code	observations	investment ($\lambda = 20\%$)	innovation	Added Value	Emission Intensity
15	64	.36	0	0	.018
31	157	.17	0	.001	.004
14	50	.26	0	.001	.005
32	293	.34	.03	.002	.07
18	130	.12	0	.002	.009
13	1644	.29	0	.006	.029
27	572	.4	.08	.007	.066
26	167	.26	.34	.008	.006
25	1147	.3	.05	.009	.019
16	1990	.32	0	.01	.083
12	207	.56	.09	.016	.002
22	998	.32	.1	.018	.019
11	1457	.55	0	.029	.007
30	640	.45	.27	.039	.002
21	1120	.48	.02	.052	.005
17	8225	.55	.01	.059	.081
10	8342	.42	0	.061	.056
28	937	.53	.26	.062	.002
19	1493	.47	.05	.072	.205
24	4947	.46	.08	.1	.038
23	22026	.37	.04	.106	.214
20	7348	.5	.17	.141	.055
29	1182	.48	.65	.201	.005

Cross-sectoral comparison of investment, innovation, Value added and aggregate Emission intensity across countries. For the latter two variables, the averages of 2005 to 2008 is taken, prior to phase 2 of EU ETS. I depict the share of the country in the total. Investment and innovation document the share of firms engaging in either in throughout the period.

These aggregate statistics point towards some interesting patterns. Clean Innovation is much more apparent in specific industries, while investment is not bound to a specific industry to the same extent. More value added sectors invest more than those that do not.

D.5 Investment or Innovation

The rising reduction in emission intensity is associated with a increasing number of patents in clean technology DechezleprÃªtre and Sato (2017), mainly for firms that are present in the EU ETS.

I examine the patent applications for firms participating in the EU ETS and compare it with the investment indicator as driving factor of the reduction of emission intensity on the idiosyncratic, firm level. The data on patent applications is sourced from PATSTAT. The classification of these patents as 'green patents' is based on the OECD classification. Since the analysis focuses exclusively on large, internationally oriented firms, I only consider those that have applied to the European Patent Office. The patent application data is then matched by name and address with firms active in the EU ETS.

A simple descriptive analysis on the patent classification is presented in Table D.4. The table reveals two key findings that are consistent with the existing literature on innovation(Acemoglu et al., 2018; DechezleprÃªtre et al., 2018). First, it confirms the idea that firms applying for patents are typically in the upper tail of the size distribution, measured by the median of value added, with the value being almost ten times higher than the non-median. Second, the median innovating firm is also significantly cleaner than its the non-innovating firm, highlighting the importance of path dependency in this variable as well.

Table D.4: Descriptive statistics 'innovators'

	Added Value (mil.)	Emission Intensity	Invested
Does not innovate	14.49	0.16	47.6 %
Does innovate	94.42	0.04	42.4 %

Median levels of Added value (deflated on the country - Nace 2 level with 2008 as 100%), Emission intensity, and the percentage of innovators which can be classified investor according to the the baseline classification I use throughout the text. Innovators

Table D.4 demonstrates that the average innovating firm is very different from the average investing firm. Approximately 33% of all firms in the EU ETS has invested at least once, while only 8% of these firms has engaged in innovation through the application of patents. This suggests that there are different drivers at play that explain the dynamics for the reduction in emission output. In a model where carbon innovation is the driving factor. As mainly clean, productive firms innovate, this would cause the distribution of clean technology to diverge, where innovators slowly take over the market share. This goes against the findings in the data however where the distribution of clean technology is converging.

To check which firm is the main driver of emission reductions, I decompose and examine the reduction of aggregate emission intensity in greater detail. Table D.5 documents the reduction for 4 types of firms and shows that the biggest reductions happened by Investors rather than innovators. The aggregate values are depicted, percentage changes are shown in brackets.

Table D.5: Emission Intensity change 2008 to 2017

		Innovators	
		Yes	No
Investors	Yes	-0.28	-0.14
		(-0.29)	(-0.28)
	No	-0.08	-0.01
		(-0.22)	(-0.03)

Aggregate reduction in Emission itensity decomposed by being either classified as investor (At least 1 investment given the baseline specification) or innovator (At least 1 patent application by EPO).

This section is not to suggest that innovation is unimportant. However, it demonstrates that the firms reducing their emissions are not always the ones driving innovation in clean technology; instead, these investors may be sourcing innovations from others. In simpler terms, the firms developing less polluting cars are not necessarily the ones purchasing them to become cleaner.

D.6 Additional regressions

This section presents additional regressions to complement the baseline cross-sectional linear probability model discussed in subsection 3.4. These additional specifications serve as robustness checks for both the choice of the investment indicator and the sample selection. First, as demonstrated in subsection D.3, various iterations of the investment indicator yield similar outcomes in terms of occurrence and their relationship with fixed capital. However, it is worth exploring how the elasticities of firm characteristics and carbon prices vary across different indicators. Second, I will implement various sample restrictions to mitigate the influence of potential outliers and other demand factors on the regression outcomes. This approach aims to enhance the reliability and robustness of the analysis.

D.6.1 Firm characteristics

This section revisits the findings presented in Table 2 and analyzes the periods before and after 2012 separately, employing various sample specifications. I focus on various functional forms as well as threshold values of the investment indicator. The results are

Table D.6: Invested before 2012

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Baseline	*Intensive*	FF2	FF3	FF4	$\lambda = 10\%$	$\lambda = 30\%$
ln_va	0.028***	0.038***	0.028***	0.031***	0.035***	0.040***	0.012**
	(0.005)	(0.011)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
ln_Emission_intensity	0.078***	0.049***	0.085***	0.082***	0.086***	0.104***	0.061***
	(0.007)	(0.009)	(0.008)	(0.007)	(0.008)	(0.007)	(0.006)
ln_allocatedtotal		-0.013					
		(0.013)					
Observations	2,437	1,950	2,437	2,437	2,437	2,437	2,437
Adjusted R-squared	0.122	0.060	0.138	0.127	0.146	0.186	0.081
Country-Sector F.E	✓	✓	✓	✓	✓	✓	✓
Clustered S.E.	C-S	C-S	C-S	C-S	C-S	C-S	C-S

Additional results for the comparison between investors and non-investors (Equation 6). The dependent variable denotes whether the firm has invested at least once throughout the sample period prior to 2012 . Standard errors are clustered on the country-sectoral level and given in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The data are the average date spans from 2005 to 207. Regression (1) denotes the baseline result and specification (2) adds the share of allocated certificates. Specification (3)-(5) resume the benchmark specification for 3 different functional forms, and specification (6) - (7) for the thwo threshold values.

To see whether the results are driven by the empirical methodology, I set up various robustness tests.Table D.6 presents the results for a sum of alternate specifications of the estimation procedure to strengthen the robustness of the results. Specification (1) resumes the earlier, baseline, regressions, also visible in Table 2. All other regressions are variations of this analysis with the last 3 focusing on the construction of the indicator itself.

The findings remain robust when including the extensive margin, employing other fixed effects or employing a variation of the investment indicator. with different threshold values ($\lambda = 10\%, 30\%$). As shown in Figure 4, the tighter the cutoff of the investment indicator, the less frequent the occurrence of what can be considered an investment. Including the share of allocated certificates reduces the probability to invest, but this might due to other confounding factors that happened during this period as it fell in the middle of the financial crisis.

Table D.7: Invested after 2012

	(1)	(2)	(3)	(4)	(5)	(6)
	Baseline	*Intensive*	FF2	FF3	FF4	$\lambda = 10\%$
ln_va	0.036***	0.054***	0.046***	0.042***	0.046***	0.058***
	(0.007)	(0.010)	(0.008)	(0.007)	(0.007)	(0.008)
ln_Emission_intensity	0.051***	0.047***	0.056***	0.053***	0.052***	0.059***
	(0.006)	(0.011)	(0.007)	(0.007)	(0.007)	(0.008)
ln_allocatedtotal		0.002				
		(0.016)				
Observations	2,623	2,037	2,623	2,623	2,623	2,623
Adjusted R-squared	0.083	0.098	0.094	0.080	0.098	0.114
Country-Sector F.E	✓	✓	✓	✓	✓	✓
Clustered S.E.	C-S	C-S	C-S	C-S	C-S	C-S

Additional results for the cross-sectional comparison between investors and non-investors (**??**). I compare the situation from 2011 - 2012 and examine the difference between firms who are going to invest in between 2013 and 2018. Standard errors are clustered at the country-sector level and given in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Regression (2) denotes the baseline result, also presented in Table 2. Regression (3) - (6) highlight several alternative functional forms of the investment indicator

The results for the period post 2012 are shown in Table D.7. Firms that invest in clean technology are on average larger, and have a higher level of emission intensity. This result supports the idea that the decision is an investment decision where more polluting firms catch up as expected by the EU government. A one percentage increase in emission intensity makes the probability that the firm invests in clean technology 0.5% more likely. Moreover, the share of freely allocated certificates does not seem to be internalized by the firms in their investment decision. Since this is ex-ante determined and does not depend on any endogenous decisions by the firm (as long as the firms remain in operation in the home country), it does not affect the margin profit of the firm.

D.6.2 The signaling function of price

To see whether firms internalize the imposed taxation in their investment decision rather than invest for other reasons, I conduct the regression. The first four specifications in Table D.8 replicate the baseline results that are given in Table 3 where the price of carbon drives the decision to invest. This section verifies its robustness to alternative specifications, both of the regression and the investment indicator.

Table D.8: Signalling function price: alternative regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				FF2	FF3	FF4	$\lambda = 10\%$	$\lambda = 30\%$
interact_P	0.001***	-0.000	0.002*	0.003**	0.003**	0.004***	0.000	0.002*
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
interact_nm_EPS	-0.004	0.012	-0.003	0.002	0.013	0.006	0.018	0.003
	(0.002)	(0.010)	(0.003)	(0.013)	(0.012)	(0.013)	(0.012)	(0.009)
interact_oil	0.001	-0.001	-0.003	0.000	-0.002	-0.001	-0.000	-0.004
	(0.001)	(0.005)	(0.005)	(0.007)	(0.006)	(0.007)	(0.006)	(0.005)
Observations	21,185	21,185	21,185	21,185	21,185	21,185	21,185	21,185
Adjusted R-squared	0.046	0.065	0.067	0.116	0.105	0.166	0.079	0.073
Year-Country F.E.	-	✓	-	✓	✓	✓	✓	✓
Year-Sector F.E.	-	-	✓	✓	✓	✓	✓	✓
Firm F.E.	✓	✓	✓	✓	✓	✓	✓	✓
Clustered S.E.	Firm	Firm	Firm	Firm	Firm	Firm	Firm	Firm

The effect of the price of carbon emissions on the investment decision (Equation 7). Standard errors are clustered at the firm level and in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Data from 2007 to 2018. Regression (1) to (3) present the results for each price variable individually and (4) shows them together. Specification (5) to (9) display robustness tests for the inclusion of several variations of the investment indicator (either for the functional form or the threshold value).

I start by examining various regression specifications in Table D.8. Regression (1) to (3) denote the elasticity of the logarithm of the individual price variables of carbon certificates, shifts in market-based policies, and the world crude oil price. The latter is included to see whether the results are not driven by omitted variable bias. All the results point towards the fact that firms invest more when the price of carbon is higher. This table also explores whether the choice of the indicator of investment matters on the impact of the price of carbon certificates on the investment decision. The threshold has to be high enough for the indicator not to capture random distortions.

To rule out potential distortions in the second phase due to coincidence with the financial crisis, I specifically focus on the situation post 2012. Table D.9 show the results for the impact of price post 2012. The elasticity of the investment decision is on average larger than over the whole sample.

D.6.3 Extensive margin - This is still under construction

One major concern voiced by many European policymakers is the risk of potential of carbon leakage, where there is a reallocation of production processes to regions with less stringent carbon regulations. This phenomena can happen directly, through the relocation of plants towards these regions, or indirectly, through the increased import of carbon-intensive goods from abroad. This empirical section focuses on the former and examines how the exit of multinational firms has evolved as a function of the initial characteristics of the firms. As the direct impact is significantly more costly for firms, one might assume that there exists

Table D.9: Signalling function price: Post 2012

	(1)	(2)	(3)	(4)	(5)	(6)
					$\lambda = 10\%$	$\lambda = 30\%$
interact_P	0.033**			0.032*	0.017	0.044***
	(0.014)			(0.018)	(0.021)	(0.016)
interact_oil		-0.009		0.004	0.005	0.017
		(0.014)		(0.015)	(0.018)	(0.013)
interact_nm_EPS			-0.003	0.005	0.004	-0.006
			(0.013)	(0.014)	(0.017)	(0.013)
Observations	12,611	11,169	11,401	11,169	11,169	11,169
Adjusted R-squared	0.129	0.126	0.122	0.126	0.148	0.115
Year-Country F.E.	✓	✓	✓	✓	✓	✓
Year-Sector F.E.	✓	✓	✓	✓	✓	✓
Firm F.E.	✓	✓	✓	✓	✓	✓
Clustered S.E.	Firm	Firm	Firm	Firm	Firm	Firm

The effect of the price of carbon emissions on the investment decision (Equation 7). Standard errors are clustered at the firm level and in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Data from 2012 to 2018. Regression (1) to (3) present the results for each price variable individually and (4) shows them together. Regression (5) and (6) show the results for different threshold values of λ.

some indirect effects as well. The latter can be inferred from the structural model.

I differentiate the exit decision between (i) the decision to exit for all firms and (ii) the exit decision for multinational subsidiaries - i.e firms that are part of a multinational that does not have its headquarters in Europe. The latter I consider the most likely firms to be affected by carbon leakage. The reason behind this choice is the fact that it is highly expensive for firms to exit their home country and move abroad. Either firms just exit the market completely and leave it to other firms - potentially from abroad -to step in and reap up the market share. The firms most likely to exit because of the carbon policy are those that already have resources somewhere upon which they are able build, either through new plants or through relocation of production to already existing plants.

Table D.10 presents the results for how the characteristics of multinational firms affect the decision to exit. The impact

Table D.10: Firm exit: firm characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$Exit^{<2012}$	$Exit^{<2012}_{multi}$	$Exit^{<2012}_{multi}$	$Exit^{<2012}_{multi}$	$Exit^{>2012}$	$Exit^{>2012}_{multi}$	$Exit^{>2012}_{multi}$	$Exit^{>2012}_{multi}$
ln_va	-0.053***	-0.008***	-0.005	-0.004	-0.035***	-0.002	-0.002	-0.002
	(0.012)	(0.002)	(0.004)	(0.003)	(0.005)	(0.002)	(0.002)	(0.001)
ln_allocatedtotal	-0.009	0.003**	0.003	0.001	0.003	0.003*	0.003*	0.002*
	(0.006)	(0.001)	(0.002)	(0.001)	(0.004)	(0.002)	(0.002)	(0.001)
Observations	1,934	726	726	726	2,067	891	891	891
Adjusted R-squared	0.104	-0.204	0.007	0.006	0.066	0.094	0.010	0.014
Country F.E.	-	-	✓	✓	-	-	✓	✓
Sector F.E.	-	-	✓	✓	-	-	✓	✓
Country-Sector F.E	✓	✓	-	-	✓	✓	-	-
Clustered S.E.	C-S	-	Bootstrap	Bootstrap	C-S	-	Bootstrap	Bootstrap

Cross-sectional regression of the impact of the initial characteristics on the probability to exit (Equation 7). Standard errors are clustered at the firm level and in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Specification (1) - (4) examine the effect of the conditions between 2005 to 2007 on the probability to exit prior 2012. the first regressions focuses on the total sample of exiters while the other 3 document the effect among multinational firms. Regression (3) and (4) are bootstrapped as the sample was too small to include clustered standard errors. Specification (5) - (8) examine the same as the first 4, but for characteristics from 2011 to 2012 on the probability to exit during phase III of the policy.

E. Accompanying notes structural model

E.1 Calibration

E.1.1 Balanced growth prior to phase II

I calibrate the model on the situation between 2005 and 2007. And consider the economy in a balanced growth situation. Here, firms do not take the price ζ_t into account in their profit maximization function. This simplifies the calibration routine severely as now it boils down to a simple Melitz-type model where productivity z is the only state variable. A few parameters require some additional information hence this section.

A) Variance productivity Since $\zeta, \kappa = 0$, the prices of each good simplify to a constant markup over marginal cost. $p = \eta/(\eta-1)1/exp(z)$

$$log(q) = -\eta log(\eta/(\eta-1)) + \eta z + \eta log(P) + Q \quad \text{(E.38)}$$

The variance of log q is solely a function of the idiosyncratic productivity as all other values are constants. Therefore:

$$var(log(q)) = \eta^2 var(z) \tag{E.39}$$

Under the assumption of $\eta = 6$. Since the variance of real output equals $var(log(q)) = 1.9$, the variance of $z = 0.31$. The mean of z is normalized to 0.

B) Variance clean technology The variance of the inverse of clean technology is directly given by the variance of the logarithm of emission intensity, which is $var(s_0) = 1.84$

C) Correlation productivity and clean technology The create the correlation the data points towards $corr(s_0, z_0) = 0.2$ at the beginning of the transition.

$$corr(s_0, log(q_0)) = \frac{cov(s_0, log(q_0))}{\sqrt{var(s_0)}\sqrt{\eta^2 var(z_0)}} = \frac{cov(s_0, log(q_0))}{\eta\sqrt{var(s_0)}\sqrt{var(z_0)}} \tag{E.40}$$

Since η is non-negative, the denominator thus of the correlation can be easily computed since both variances are known. The covariance itself is a covariance between s_0 and productivity z_0 given a constant value, which drops out.

$$cov(s_0, log(q_0)) = cov(s_0, -\eta log(\eta/(\eta-1)) + \eta z_0 + \eta log(P) + Q) = cov(s_0, \eta z_0) = \eta cov(s_0, z_0) \tag{E.41}$$

Thus the correlation between clean technology and output also directly provides the correlation between clean technology and productivity as long as the output factor does not depend on the level of clean technology s due to the taxation $\zeta > 0$, which is the case during the transition.

$$corr(s_0, log(q_0)) = corr(s_0, z_0) = \frac{cov(s_0, z_0)}{\sqrt{var(s_0)}\sqrt{var(z_0)}} \tag{E.42}$$

D) Head-Ries Index To measure the cross-border trade costs τ_{gj} I use the Head and Ries (2001) index, extended by AntrÃ s and Chor (2018) to the industry level. The index uses the observed values of bilateral trade flows relative to the domestic absorption to infer the cross-border costs. I compute the following:

$$\tau_{gjt} = \left(\frac{X_{gjt}X_{jgt}}{X_{ggt}X_{jjt}}\right)^{-\frac{1}{2\gamma}} \tag{E.43}$$

for each $g, j \in (d, f)$, $j \neq g$ and the time index $2007 \geq t > 2005$. The variables X_{gg} and X_{jj} denote the domestic absorption and $\gamma > 1$ is the trade elasticity with respect to the iceberg trade cost. In this setting, I follow AntrÃ s and Chor (2018) and adopt a value of $\gamma = 5$. Note that this implies that international trade costs are equal to 1 and that trade costs are symmetric $i.e. \tau_{gj} = \tau_{jg} = \tau$. The time index is capped to be between 2005 and 2007 in order not to get deluded with the taxation from the home government ζ and κ. I assume that the distribution of productivity is orthogonal to the country and all variation in the output by country is captured through differences in marginal cost. This also means that $\tau_{gj} > 1$ for $g \neq j$.

E.1.2 Transition 2008 - 2018

Minimizing moments I calibrate the transition part of the model on the occurrences of the investment decision and the probability to exit the economy for multinational firms. To minimize the the moments, I minimize the following absolute loss function:

$$min \sum_j abs\left(\frac{X_j^D - X_j^M}{X_j^D}\right) \tag{E.44}$$

Where X_j^D and X_j^M denote the corresponding j moment in the data and model respectively. The function is both less sensible to huge errors and of independent of the scale of the variable relative to other loss functions.

E.2 Validation model results

E.2.1 Regression results model

Table E.11: firm characteristics in model

	(1)	(2)	(3)	(4)
VARIABLES	Clean tech.	Emis. Intens.	Cross-section	Cross-section
log_pi	0.003***	0.003***	0.047***	0.035***
	(0.000)	(0.000)	(0.002)	(0.002)
ln_emission_intensity	0.02***		0.027***	
	(0.000)		(0.002)	
ln_clean_technology		-0.052***		-0.318***
		(0.006)		(0.055)
Observations	59,940	59,940	4,995	4,995
Adjusted R-squared	0.690	0.690	0.054	0.050
Year fe	✓	✓	-	-

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

The following two tables are the equivalent of **??** and **??** for a dataset of 100 000 firms generated by the model. The analysis omits all firms operrating abroad and all firms that decide to relocate abroad to get a balanced panel of firms that operate in the home country.

Table E.12: firm characteristics in model

VARIABLES	(1) Clean tech.	(2) Emis. Intens.	(3) Clean tech.	(4) Emis. Intens.	(5) Emis. Intens.
ln_p	0.034***	0.047***			
	(0.004)	(0.006)			
interact_P	0.108***		0.108***		
	(0.016)		(0.016)		
interact_P_EI		0.004***		0.004***	0.003***
		(0.001)		(0.001)	(0.001)
Observations	54,945	54,945	54,945	54,945	44,955
Adjusted R-squared	0.605	0.605	0.605	0.605	0.579
Year fe	✓	✓	✓	✓	✓
Firm fe	✓	✓	✓	✓	✓
Clustered S.E.	firm	firm	firm	firm	firm

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

E.2.2 Inequality Data

Figure E.8 illustrates how the standard deviation of the logarithm of labor and emission intensity has evolved over time in the dataset. A linear fit of the evolution is represented by the dotted line. In the right panel of the figure, the evolution of the distribution of the logarithm of clean technology and labor in the model is displayed. Notably, both evolutions, observed in both the model and the actual data, demonstrate a consistent pattern, thereby reinforcing the model's findings. Note that the evolution of emission intensity cannot be interpret as an evolution in clean technology through the presence of the price pass through, but it is reassuring to note that both still exhibit similar evolutionary trends.

E.3 Comparative statics

F. Other

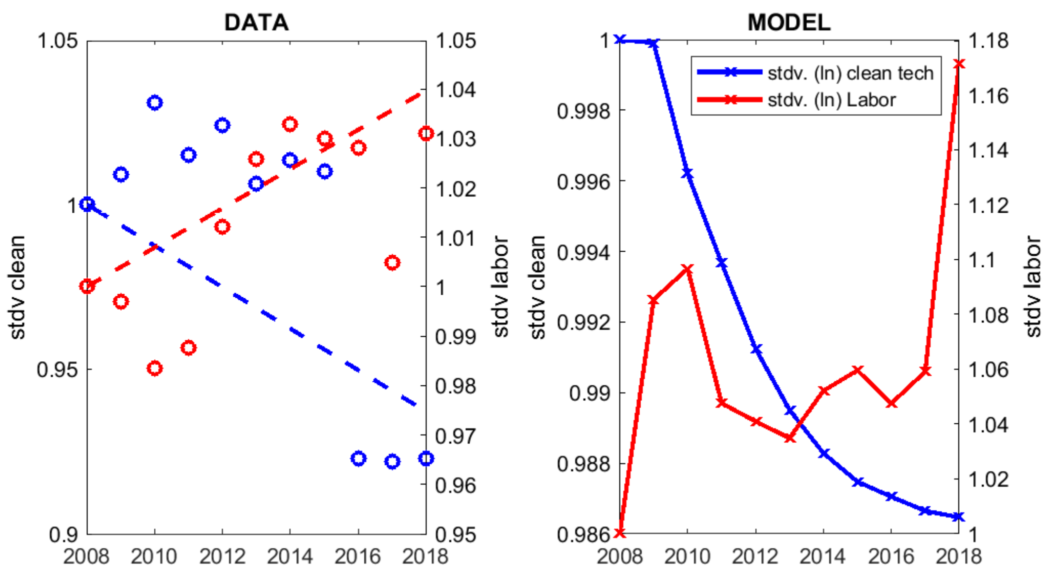


Figure E.8: Inequality Evolution

Evolution of standard deviation of the logarithm of labor and clean technology (emission intensity in the data) for the data and the model.