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Does pricing carbon mitigate climate change? Firm-level evidence from the European Union emissions trading scheme

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Abstract

In theory, market-based regulatory instruments correct market failures at least cost. However, evidence on their efficacy remains scarce. Using administrative data, we estimate that, on average, the EU ETS – the world's first and largest market-based climate policy – induced regulated manufacturing firms to reduce carbon dioxide emissions by 14-16% with no detectable contractions in economic activity. We find no evidence of outsourcing to unregulated firms or markets; instead firms made targeted investments, reducing the emissions intensity of production. These results indicate that the EU ETS induced global emissions reductions, a necessary and sufficient condition for mitigating climate change. We show that the absence of any negative economic effects can be rationalized in a model where inattentive firms underinvest in energy-saving capital prior to regulation. Guided by the predictions of this model, we classify firms with low initial productivity or high energy intensity as potentially inattentive. We estimate larger reductions in emissions and increases in economic activity for those firms, consistent with regulation-induced cost savings or efficiency increases.

Keywords: cap-and-trade, carbon leakage, investment, climate policy

JEL Classifications: Q54 Q58, H23, L50, F18.

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Non-technical summary

The unchecked accumulation of greenhouse gas (GHG) emissions is one of the starkest examples of market failure worldwide: a by-product of valuable economic activities, their costs are not fully accounted for in economic decision-making. Regulatory instruments are therefore proposed to correct this and in theory, market-based policies, such as a carbon tax or trading scheme can do so at least cost. They discourage the production of emissions-intensive goods by putting a price on emissions and encouraging both emissions abatement, in particular by emitters with low abatement costs, and investments in technology that lowers abatement costs. Different compliance strategies by firms have very different implications for the economy and the global environment. Flexibility in how to comply may lead to leakage effects that undermine climate change mitigation: for example, if regulated firms cut emissions by outsourcing carbon-intensive elements of the value chain, then carbon emissions will simply 'leak' to unregulated jurisdictions or to unregulated firms or market segments within the same jurisdiction. This paper provides evidence on the environmental and economic consequences of a carbon market by evaluating the European Union Emissions Trading Scheme (EU ETS) – the world's first and largest market-based climate policy. Introduced in 2005, the EU ETS establishes a price for the right to emit carbon dioxide (CO_2) emissions to more than 12,000 power and manufacturing plants in 31 countries. Using administrative data for France between 2005 and 2012, we estimate that, on average, the EU induced regulated manufacturing firms to reduce CO_2 emissions by 14-16% with no detectable contractions in economic activity. We find no evidence of outsourcing to unregulated firms or markets; instead firms made targeted investments, reducing the emissions intensity of production. These results indicate that the EU ETS induced global emissions reductions, a necessary and sufficient condition for mitigating climate change. We also show that the absence of any negative economic effects can be rationalized in a model where inattentive firms under-invest in energy-saving capital prior to regulation. Guided by the predictions of this model, we classify firms with low initial productivity or high energy intensity as potentially inattentive. We estimate larger reductions in emissions and increases in economic activity for those firms, consistent with regulation-induced cost savings or efficiency increases.

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1 Introduction

The unchecked accumulation of greenhouse gas (GHG) emissions is one of the starkest examples of market failure worldwide. GHG emissions are a by-product of valuable economic activities. However, the costs they impose through climate change are not fully accounted for in economic decision-making. In theory, market-based regulations hold the promise of mitigating climate change at least cost to society (Pigou, 1920; Baumol & Oates, 1971; Baumol, 1972; Montgomery, 1972; Tietenberg, 1973; Nordhaus, 1977; Hahn, 1989; Nordhaus, 2001; Burke et al., 2016; Gillingham & Stock, 2018).[1] These regulations discourage the production of emissions-intensive goods by putting a price on emissions. The price encourages both emissions abatement, in particular by emitters with low abatement costs, and investments in technology that lowers abatement costs.

Market-based regulations allow polluting firms more flexibility in choosing their own path to compliance than command-and-control regulation, yet different compliance strategies have very different implications for the economy and the global environment. Flexibility in how to comply may lead to leakage effects that undermine climate change mitigation. If regulated firms cut emissions by outsourcing carbon-intensive elements of the value chain, then carbon emissions will simply 'leak' to unregulated jurisdictions or to unregulated firms or market segments within the same jurisdiction. Carbon leakage threatens the efficacy of any unilateral climate change mitigation policy by limiting, or even reversing, its impact on global emissions.

This paper provides evidence on the environmental and economic consequences of market-based regulations to mitigate climate change by evaluating the European Union Emissions Trading Scheme (EU ETS) – the world's first and largest market-based climate policy. Introduced in 2005, the EU ETS establishes a price for the right to emit carbon dioxide (CO_2) emissions. This is achieved by imposing a cap on the aggregate emissions from more than 12,000 power and manufacturing plants in 31 countries. The cap covers 45% of EU emissions and 5% of global emissions. Tradeable permits are then issued for each tonne of CO_2 under the cap. The permit price is formed in a European wide market where firms with a permit surplus sell to firms that require permits in order to comply with the regulation.

Whether such a cap-and-trade scheme reduces emissions is a question of regulatory stringency and the extent to which emissions are relocated to unregulated jurisdictions. That is, emissions

[1] While there is plenty of disagreement among economists in discussions of policy and government intervention, a preference for market-based regulatory instruments is a point in which economists largely agree. On January 17th 2019, over 3,500 economists, from a diverse set of political, ideological, and academic backgrounds, rallied around the efficacy of market-based mechanisms for internalizing the social costs of climate change in a statement published in the Wall Street Journal – the largest public statement by economists in history. The second largest public statement by economists was the "Economists' Statement on Climate Change" signed by 2,500 economists in 1997 at the time of the Kyoto Protocol, calling for market-based mechanisms to mitigate climate change.

within the regulated market must be lower than if the cap did not exist. In lieu of this unobservable condition, economists view a high and stable permit price as a credible signal of regulatory stringency. During Trading Phase I (from 2005 until 2007), permit prices first climbed to $37 before collapsing to less than $1 in early 2007. However, permit prices rebounded to around $21.35 ($2017) during Trading Phase II (between 2008 and 2012). Whether these prices were sufficient to deliver meaningful reductions in regulated emissions, and whether these reductions were offset by increases in unregulated emissions, are empirical questions. We seek to answer these questions using comprehensive administrative data from the French manufacturing sector.

Using a matched difference-in-differences research design, we estimate that the EU ETS induced regulated firms to reduce CO_2 emissions relative to unregulated firms by 14%, during Trading Phase I and by 16% in Trading Phase II with no detectable negative effects on economic output or employment. We estimate no significant effects prior to the announcement of the EU ETS or during the announcement period. On aggregate, our results imply that CO_2 emissions fell by 5.4 million tonnes on average between 2005 and 2012, accounting for approximately 28-47% of the aggregate reduction in industrial emissions during this period.

We also provide evidence indicating that the EU ETS induced global emissions reductions, which is the relevant outcome from the perspective of climate change mitigation. First, as noted we estimate no detectable negative effects on the economic performance of regulated firms. If we found such effects, this could mean that the policy shifted production and emissions to unregulated firms. Counter to this leakage mechanism, we estimate significant reductions in the CO_2 intensity of value added, but no effect on value added or employment. Second, we find no evidence that firms increased imported inputs or the carbon content of inputs through trade. Nor do we estimate increased substitution towards purchased electricity or a change in the composition of emissions. These findings are inconsistent with carbon leakage being a first-order driver of the estimated emissions reductions in this context. Instead, we present evidence that investments in cleaner production processes was the prevailing abatement mechanism among regulated firms.

How could firms reduce emissions without any detectable contraction in economic activity despite the fact that carbon pricing increases input costs? Under standard assumptions, a model of firm production predicts contractions in economic activity alongside reductions in emissions (possibly accompanied by decreasing effects on productivity, cf. Greenstone et al., 2012). Contrary to this, we find that ETS participation is associated with weakly positive effects on value added, employment and investment. One hypothesis is that the ETS induced firms to make investments that increased productivity, offsetting the regulatory costs to the firm. We present an augmented model of firm production that allows for high substitutability between energy and clean capital as well as the possibility that firms are inattentive towards the returns on such clean capital. These extensions deliver the potential for under-investment prior to the introduction of costly regulations. In support of this interpretation, additional results show that low productivity/high emissions intensity firms, those we conjecture are most inattentive, experience expansions in value added alongside emissions reductions.

The maximum permit price during the time of the estimated emissions reductions suggests that marginal abatement costs could not have exceeded \$53 per tonne of CO_2 (\$2017). This price reflects the point where firms would have been indifferent between buying permits and reducing emissions and so true marginal abatement costs were likely much lower. Nevertheless, this cost compares favorably to the marginal abatement costs of many non-market based regulatory instruments (Gillingham & Stock, 2018). To the degree that these insights generalize to other markets and settings, our study highlights that market-based regulations can, in practice, be an effective and economically reasonable tool for mitigating climate change.

Our paper contributes to several literatures. First, we contribute to a literature exploring the effects of environmental regulation on firm behavior (Becker & Henderson, 2000; Greenstone, 2002; Fowlie et al., 2012; Greenstone et al., 2012; Ryan, 2012; Walker, 2013; Martin et al., 2014a,b; Fowlie et al., 2016; He et al., 2020). This literature typically focuses on the effects of policy on either economic or environmental outcomes. We evaluate treatment effects on both types of firm-level outcomes. We also provide detailed evidence on the mechanisms through which firms reduce emissions. This is essential to understand whether the policy was effective at achieving its ultimate objective, which is to reduce global emissions. We also present a new framework for evaluating the economic consequences of environmental regulations on firm behavior. This framework proves helpful for gaining a deeper understanding of the mechanisms driving our empirical results, and provides guidance for future research in this area.

Second, we contribute to a growing empirical literature seeking to understand the effects of the EU ETS itself (see Martin et al., 2016, for a more detailed review). Early studies in this area have been at the country or sector-level, which complicates causal inference due to confounding factors (Ellerman & Feilhauer, 2008; Ellerman et al., 2010; Egenhofer et al., 2011; Andersen & Di Maria, 2011). Most relevant to our study is a strand of the literature that employs difference-in-differences designs akin to Fowlie et al. (2012) in order to evaluate the impacts of the EU ETS on manufacturing firms.[2] A robust finding across studies is the absence of detrimental effects on economic performance, broadly defined (Jaraite & Di Maria, 2016; Marin et al., 2018; Dechezleprêtre et al., 2023; Löschel et al., 2019; Klemetsen et al., 2020; Gerster et al., 2021). The available evidence on industrial CO_2 emissions is not conclusive, however, and results vary across countries and trading phases. Specifically, emissions reductions were estimated for Norway (Klemetsen et al., 2020) but

[2]Beyond manufacturing, researchers have estimated the impact of the EU ETS on power plants (Fabra & Reguant, 2014; Zaklan, 2021), on patenting (Calel & Dechezleprêtre, 2016), and on foreign direct investment (Koch & Basse Mama, 2019; Borghesi et al., 2020).

not for Germany (Gerster et al., 2021) or Lithuania where CO_2 intensity fell (Jaraite & Di Maria, 2016). The EU ETS was found to have no impact on CO_2 intensity in the United Kingdom (Calel, 2020), though it may have reduced CO_2 emissions in that country, according to a study of selected emitters in four EU countries (Dechezleprêtre et al., 2023). The tightening of the EU ETS in more recent years has come with improvements in the emission efficiency of the biggest emitters (De Jonghe et al., 2020).

These studies are valuable because they establish under which conditions the EU ETS induced local reductions in emissions. The principal limitation in previous research is a lack of compelling evidence on the mechanisms through which emissions reductions were delivered. Yet understanding the mechanisms is crucial if we are to rule out the possibility that local emissions reductions did not translate into global reductions, which is a necessary and sufficient condition for mitigating climate change. Our study fills this gap. Using linked administrative data from multiple sources, not only do we estimate the effects of the EU ETS on the emissions and economic performance of firms, but we also identify how firms respond to comply with the regulation. In so doing, we provide the first evidence in support of the proposition that the EU ETS, the most significant climate policy instrument to date, has delivered on its stated policy objective.

Finally, we provide early empirical evidence that market-based mechanisms are a cost-effective way of reducing emissions. In recent years there has been renewed interest in understanding which government interventions are most effective at improving social welfare (Hendren & Sprung-Keyser, 2020; Hendren & Finkelstein, 2020); however, evaluating the welfare effects of regulations faces a number of theoretical and empirical challenges given the need to weigh the benefits to society against the costs to firms and workers. Our findings indicate that the EU ETS delivered global emissions reductions with no detectable economic contraction. Understanding the efficacy of government interventions is especially important in the context of mitigating global climate change, due to the severity of the problem and due to the limited resources available to tackle it. We posit that the emissions reductions induced by the EU ETS likely cost substantially less per tonne of CO_2 than alternative non-market-based regulatory instruments (Gillingham & Stock, 2018).[3]

In the next section, we describe the design of the EU ETS and our empirical approach. Section 3 describes the data used for analysis. Section 4 presents the main results and Section 5 explores the underlying mechanisms. Section E present back-of-the-envelope calculations that consider the contribution of the EU ETS to aggregate emissions reductions and compares the cost-effectiveness of the EU ETS to other existing and proposed climate change mitigation policies. Section 7 con-

[3]This conclusion only holds for the manufacturing sector considered here; a system-wide assessment of abatement costs is beyond the scope of our study. Moreover, as noted by Vogt-Schilb & Hallegatte (2014), command-and-control policies might deliver better results if emissions-reducing investments are subject to strong path dependencies, requiring that expensive abatement investments be made before reaping low-hanging fruit. We thank two anonymous referees for raising these caveats.

cludes.

2 Evaluating the European Union Emissions Trading Scheme

Identifying the causal effects of a real-world policy intervention is never a trivial exercise. In the context of the EU ETS, two major challenges arise. First, accurate data on carbon emissions prior to the implementation of the ETS is scarce, as most countries did not explicitly collect this information before it was required for monitoring purposes.[4] However, pre-implementation data is required to establish that any measured change in the performance of regulated firms can plausibly be ascribed to the policy itself, and not to other factors. With access to rich administrative data on the fuel use of French manufacturing plants, we are able to construct a consistent, bottom-up measure of direct emissions for all firms, including unregulated ones, both before and after the implementation of the EU ETS. Each dataset as well as the linkages are explained in detail in Section 3 below.

Second, to evaluate the effects of any policy, it is important to have a credible counterfactual. This is particularly challenging in the absence of experimental conditions in which subjects can be randomly assigned to treatment and control groups. Correlation does not imply causation. There are many reasons why emissions could have fallen since the implementation of the EU ETS. Emissions in Europe have been declining for some time, as a result of structural economic change and due to energy efficiency improvements. Furthermore, the Great Recession resulted in a significant drop in economic activity, which in turn likely contributed to at least temporary declines in greenhouse gas (GHG) emissions in the EU and around the world. These trends make the evaluation of emissions trading schemes at the aggregate level (i.e., country or sector) a futile exercise, because it is not possible to disentangle the effects of policy changes from other changes over time.

It is only through the combination of temporal and cross-sectional variation in treatment assignment among otherwise similar firms that one can hope to identify the causal effect of the EU ETS on emissions and economic outcomes. We caveat that our estimates capture the direct effect of the EU ETS on firm behaviour. Our estimates are net of any indirect effect that the ETS has on firms. For example, we are not able to identify any common effect of the ETS that affects both the treatment and the control group, e.g., cost-pass through effects due to market-wide price increases in electricity or other carbon-intensive inputs (Fabra & Reguant, 2014; Hintermann, 2016). The remainder of this section explains why the design of the EU ETS gives rise to both types of variations and how the specific institutional details allow us to identify and estimate the direct effects

[4] Previous work on this policy has been largely unable to compare emissions before and after its introduction Ellerman & Buchner (2008); Ellerman et al. (2010); Egenhofer et al. (2011); Andersen & Di Maria (2011).

of the policy using variants of the difference-in-differences estimator.

2.1 Treatment Assignment in the EU ETS

The EU ETS is a European wide cap-and-trade program for CO_2 emissions.[5] Polluters regulated under the policy are required to surrender, at the end of each year, one European Union Allowance (EUA) for each tonne of gas they have emitted over the year. They may buy additional EUAs or sell excess EUAs on an international market at a uniform price. Within limits, EUAs can be banked or borrowed to balance needs across years. The total amount of EUAs in the system is limited and linearly declines over time. Scarce EUAs command a positive price in the permit market. The treatment effect we seek to identify is the average effect of having to pay for CO_2 emissions on various outcome variables of treated polluters. Allocation of EUAs to polluters is via free allocation or permit auctions. During the study period of this paper, free permit allocation to manufacturing firms was the rule. Our main analysis abstracts from permit allocation for two reasons. First, by a Coasian argument, permit allocation should not affect firm behavior at the margin. Second, we lack a credible strategy to test for a causal effect.

Our identification strategy exploits both temporal and cross-sectional variation in treatment assignment. The EU ETS was launched in 2005, when France and most other European countries did not have CO_2 prices in place. While this makes 2005 the first year of actual regulatory treatment, we allow for the possibility that polluters responded to the announcement of the policy before the actual launch.[6]

The EU ETS was officially announced with the publication of the Emissions Trading Directive in 2003 (Directive 2003/87/EC). However, the publication of the directive marked the culmination of a multi-year consultation process between the EU Commission and stakeholders about key design features of the policy. The process was initiated with the publication of a green paper by the EU Commission in 2000 (European Commission, 2000). Comments on the green paper submitted by businesses, NGOs and governments were published in May 2001 (European Commission, 2001). At that point, actors likely had some clarity regarding the shape that the ETS would be taking. We thus consider the year 2001 as the beginning of the announcement period.

Cross-sectional variation in treatment assignment arises because not all CO_2 emitters in Europe are regulated under the EU ETS. Participation criteria were first spelled out in the Emissions Trading Directive and then transposed into national laws.[7] These criteria are targeted at industrial

[5] Ellerman et al. (2016) provide a concise yet comprehensive review of the history and structure of the EU ETS.

[6] Since CO_2 intensities are often embodied in long-lived capital goods, such anticipated adjustments make economic sense if they prevent a polluter from being locked into high CO_2 intensities – and hence, high compliance costs – for decades to come.

[7] To harmonize criteria across countries, as well as to include additional sectors, the directive was later amended (Directive 2009/29/EC)

facilities at the sub-firm level, referred to in the directive as installations. Different criteria are defined for combustion activities on the one hand and other carbon intensive processes on the other hand.

Participation in the EU ETS is mandatory for combustion installations with a rated thermal input of 20 megawatts (MW) or more. This not only concerns fossil-fuel fired power plants, which are not analyzed in this paper, but also industrial plants across a wide range of industries which generate heat, steam or power on site. Additional industrial installations are included because they specialize in carbon intensive processes and exceed specific capacity thresholds. Process-based definitions target, *inter alia,* pulp and paper mills, coke ovens, petroleum refineries, non-metallic mineral products (including the manufacture of glass, ceramics, and cement), and the manufacture of basic metals.[8] Indirect emissions, i.e. from emissions from sources that are not owned and not directly controlled by the firm, are not taken into account, nor are electricity imports.

We match French ETS installations listed in the official trading registry to the manufacturing establishments operating them (further detail is presented in Section 3.7 below). Any establishment identified in this way is considered as treated and referred to as an ETS plant. Likewise, a firm is considered as treated and referred to as an ETS firm if it operates at least one ETS plant. We define a time-invariant definition of exposure to the ETS based on whether a firm has ever operated at least one ETS plant during the study period.

The installation-centered, capacity-based participation rules used in the Emissions Trading Directive induce variation in treatment status even among firms of similar size (Calel & Dechezleprêtre, 2016). To see this, consider as an example the case of two firms that operate combustion installations. Both firms have a total combustion capacity of 30 MW, but the distribution of that capacity across plants gives rise to different treatment assignments. Plant 2 is treated because it has a rated thermal input of 30 MW, which is above the participation threshold. Plant 1 is not regulated because it achieves the same total capacity by operating two smaller plants with rated capacity of 15 MW, which is below the threshold. Similar cases arise for process-regulated activities due to the capacity-based approach with sharp thresholds.

If the capacity ratings of plants were known to us, we could identify the treatment effect in a regression-discontinuity design. However, no such data are publicly available for France (and, to the best of our knowledge, in any other European country). Nevertheless, we can take advantage of the fact that the participation rules induce variation in treatment status across firms with similar levels of CO_2 emissions by using difference-in-differences approaches that have been successfully used in the evaluation of other cap-and-trade schemes (Fowlie et al., 2012). To internalize spillovers that may arise between regulated and unregulated plants that belong to the same firm, and to take advantage of a much larger set of firm-level outcome variables, we set out to identify

[8] Beginning in 2012, emissions from other industries, such as aviation, have been included in the ETS as well.

average treatment effects on the treated at the firm level.

Table 1 presents within-sector differences in pre-treatment characteristics between ETS and non-ETS firms in the year 2000. We see that there are large and significant differences in emissions and production between regulated and unregulated firms. While balance is not required to identify the effects of the ETS using a difference-in-differences estimator, the parallel trends assumption is more likely to hold when baseline differences between the treatment and control group are smaller. The large gaps motivate the creation of a matched analysis sample, which we use in our main analysis. We discuss the matching process below, but note that while some baseline differences remain between treated and control firms they are notably smaller than in the unmatched sample and statistically insignificant in many cases.

2.2 Matched Difference-in-Differences Approach

Having longitudinal firm data allows us to estimate counterfactual emissions in the absence of the EU ETS and thereby tease apart the effect of the regulation. We use a semi-parametric difference-in-differences approach, following Heckman et al. (1997, 1998):

$$\begin{aligned} \alpha_{ATT}^{matched} &= \mathbb{E}[Y_{it'}(1) - Y_{it'}(0) | X_i, ETS_i = 1] \\ &= \frac{1}{N_1} \sum_{j \in I_1} \left\{ (Y_{jt'}(1) - Y_{jt}(0)) - \sum_{k \in I_0} \omega_{jk}(X_j, X_k) \cdot (Y_{kt'}(0) - Y_{kt}(0)) \right\} \end{aligned} \tag{1}$$

where I_1 denotes the set of ETS firms, I_0 the set of non-ETS firms, and N_1 the number of participating firms in the treatment group. The treated firms are indexed by j, the control firms are indexed by k. The weight placed on a non-ETS firm when constructing the counterfactual estimate for ETS firm j is ω_{jk}. These weights can be calculated using any matching approach. The rationale behind matching is to improve covariate balance and to increase common support between regulated and unregulated firms. Table 1 and Figures A.3-A.4 show that our matching approach, while not perfect, substantially improves the balance and common support between regulated and unregulated firms.

In our baseline specification, we implement this approach as a difference-in-differences regression on a matched sample obtained in a one-to-one nearest-neighbor matching. We calculate the difference in average emissions for regulated firms, before and after the introduction of the EU ETS and subtracting from this change the difference in average emissions from a matched unregulated firm before and after the introduction of the EU ETS. The regression equation is given by

$$(Y_{j,t} - Y_{j,2000}) - (Y_{k,t} - Y_{k,2000}) = \sum_{\tau=1}^{4} \beta_\tau \times \mathbb{1}\{t \in \Phi_\tau\} + \varepsilon_{j,t} \tag{2}$$

Table 1: Descriptive Statistics for Regulated and Unregulated Firms

	(1) Pre-Match Unregulated (Full Sample)	(2) Pre-Match Regulated (Full Sample)	(3) Pre-Match Difference (Full Sample)	(4) Post-Match Difference (Matched Sample)
log (CO_2)	-0.043	3.715	3.758***	0.944***
	(1.757)	(1.527)	(0.100)	(0.157)
log (Employment)	5.457	6.126	0.668***	0.135
	(0.873)	(1.265)	(0.0808)	(0.0993)
log (Value Added)	9.242	10.295	1.053***	0.176
	(1.047)	(1.361)	(0.0872)	(0.120)
log (Capital Stock)	9.449	11.233	1.784***	0.444***
	(1.310)	(1.534)	(0.0987)	(0.152)
log (CO_2/VA)	2.228	4.933	2.705***	0.768***
	(1.636)	(1.395)	(0.0915)	(0.0936)
log (Total Imports)	16.052	17.139	1.087***	-0.0114
	(1.401)	(1.823)	(0.117)	(0.222)
Gas Share	0.638	0.702	0.0638***	-0.0647
	(0.440)	(0.372)	(0.0244)	(0.0592)
Electricity Bought Share	0.516	0.263	-0.254***	-0.0375**
	(0.247)	(0.188)	(0.0125)	(0.0171)
Observations in year 2000	3,949	252	4,201	298
# of Regulated Firms	0	252	252	149

Notes: Columns 1 and 2 report the mean and standard deviation of each variable for unregulated (control) and regulated (treatment) firms in the year 2000. Reported coefficients in Columns 3 and 4 measure the difference in outcome variables between treatment and control firms in that year. Column 3 presents the average difference between unmatched treatment and control firms. Column 4 presents the average difference between matched treatment and control firms. Robust standard errors reported in column 3. Two-way clustered standard errors (by firm and matching group) are reported in column 4. Units (Logarithms of): CO_2 – thousands of tonnes of CO_2; Value Added – thousands of Euros; Employment – full-time equivalent employees; Capital – thousands of Euros; CO_2/VA units – hundred thousands of tonnes of CO_2 per Euros of value added; Imports – Euros; Gas Share – CO_2 from Gas/Total CO_2; Electricity Bought Share – Purchased Electricity/Total Energy Consumed in tonnes of oil equivalent. Purchased electricity is converted from MWh to tonnes of oil equivalent using the conversion factor toe = MWh$\times$0.086. Significance levels are indicated as * 0.10, ** 0.05, *** 0.01.

where phases $\{\Phi_\tau\}_{\tau=1}^4$ are defined as,

$$\begin{aligned}
\Phi_1 &= \{1996, \ldots, 1999\} && \text{(Pre-Announcement Period),} \\
\Phi_2 &= \{2001, \ldots, 2004\} && \text{(Announcement Period),} \\
\Phi_3 &= \{2005, \ldots, 2007\} && \text{(Trading Phase I), and} \\
\Phi_4 &= \{2008, \ldots, 2012\} && \text{(Trading Phase II).}
\end{aligned}$$

The left-hand side of equation (2) denotes the difference in outcome between treated firm j and matched control firm k in year t, relative to that difference in the base year 2000, i.e. just before the announcement of the EU ETS. The coefficients of interest are $\beta_\tau = \alpha_{ATT}^{matched}$ and provide the effect of the EU ETS on regulated firms in period τ as compared to the matched control firms, and relative to the year 2000.

Matching Variables We match non-ETS firms to ETS firms along a number of dimensions. For each variable we match using data from the year 2000 (the year prior to the announcement of the EU ETS). We match on the CO_2 emissions, value added, employment, capital, emissions intensity, total imports, share of gas in CO_2 emissions, share of consumed energy that comes from purchased electricity, number of plants in the firm, and the 2-digit NCE sector of the firm, which we re-define to reflect the fact that multi-plant firms may engage in multiple activities.[9] We match exactly on sector to control for sector-specific shocks to the outcome variables that may have occurred after the introduction of the EU ETS. Within a given sector we use a nearest neighbour using a mahalanobis distance across our matching variables. Our matching variables are chosen to identify a set of comparison firms that are similar in terms of their environmental characteristics (emissions, emissions intensity), their production function (value added, labor, and capital), the composition of emissions and energy use (gas share and electricity share), and their exposure to trade (imports). We do not match on pre-treatment trends. Instead, we let the data speak to the validity of the assumption that pre-treatment trends in the outcome variables are parallel. Column 4 of Table 1 shows that the post-match difference in baseline characteristics is substantially smaller than the pre-match difference (column 3). While remaining statistically significant, the gap in emissions, capital, and emissions intensity is 75% smaller than the pre-match difference. The gap in the share of energy consumed that comes from purchased electricity is 85% smaller. There is no statistically

[9] We define a new sector variable SUPERNCE at the firm level which is based on the combination of all plant-level activities. For example, if a firm owns two plants and both produce in NCE 12, then the SUPERNCE is 12 and the firm would be matched to a control firm in the same sector (with SUPERNCE 12). In contrast, for a firm with one plant producing in NCE 12 and another one in NCE 17, we define SUPERNCE to be 1217 and match it to a control firm within SUPERNCE 1217 (where the ordering of sectoral codes does not matter, e.g., SUPERNCE "1217" is equivalent to SUPERNCE "1712").

significant or economically meaningful post-match difference in value added, employment, the composition of emissions, or imports.

Inference on Post-Matching Regression Coefficients It has been argued that matching can be seen as a pre-processing step to estimation and thus be ignored in the computation of standard errors (Ho et al., 2007). However, Abadie & Spiess (2022) show that bias in the estimation of the variance can occur if the covariates in the regression are correlated with the error term, conditional on the variables that have been matched on. They demonstrate that valid inference can be conducted if matching is done *without replacement* and standard errors are clustered at the level of the match.

Matching without replacement implies that a given control firm will only be used as a match in a given year for one particular treated firm. This has the potential downside of introducing bias in the asymptotic distribution of the post-matching regression estimator, especially when few suitable controls are available relative to the number of treated units.

By contrast, matching with replacement allows for a larger sample size because multiple treated firms can be matched to the one control firm that best fulfills the matching criteria. Given the bias-variance trade-off we give priority to the former and use matching with replacement in our main specification. To address the point made by Abadie & Spiess (2022), we use a two-way cluster adjustment. The first cluster is at the level of the match (the firm) and also addresses serial correlation. The second cluster is at the control-firm-year level to account for correlation across observations that are matched to the same control observation. We propose that this additional adjustment addresses at least part of the concern associated with the effects of matching with replacement on inference.[10] In Appendix B.2, we show that our results are robust to using matching without replacement and cluster at the firm-level in line with Abadie & Spiess (2022).

2.3 Identification Assumptions

Our econometric approach assumes that the trajectory of regulated firms would have continued to follow the trajectory of unregulated firms in the absence of the policy. We argue that this parallel trends assumption is plausible when evaluating the effects of the EU ETS using pairs of similar firms matched within narrowly defined sectors. To make this argument, it is helpful to distinguish between two potential violations of the parallel trends assumption. First, treated and control firms could be on different trajectories already before the launch of the ETS. Second, other contemporaneous shocks may differentially affect the trajectories of treated and control firms. Either violation would lead to biased inferences about the effect of the ETS. While neither assumption is testable,

[10]Notice that our adjustment collapses to the solution presented in Abadie & Spiess (2022) when each treatment firm is matched to a unique control firm. In this case the second cluster becomes redundant.

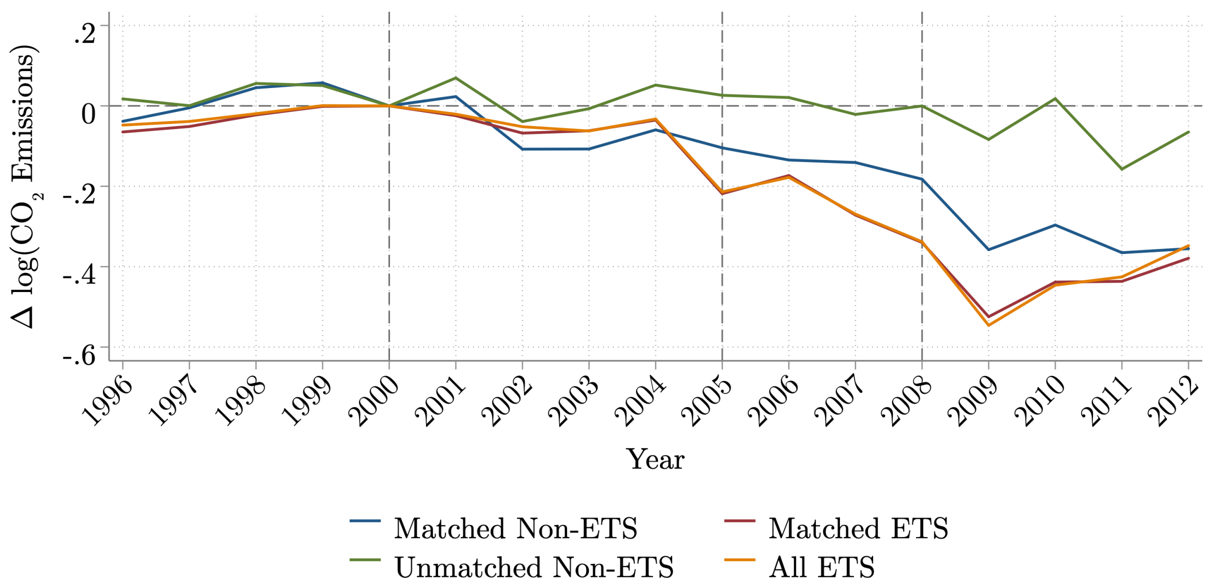
analysis can help to evaluate whether the violations are likely to be a first-order concern. For example, for observable characteristics, we should not see any differential trends between regulated and unregulated firms prior to the introduction of the ETS. Concerns related to whether other shocks that coincided with the EU ETS need to be addressed on a case-by-case basis, require institutional knowledge, and ultimately depend on the degree to which it is credible that treated and control firms were differentially affected. Where possible we engage in additional analyses to help increase the credibility of our research design.

Potential violations arise from overlapping energy policies and economic fluctuations that occurred during the treatment period. The former include energy taxes, subsidies for renewable energy, and energy efficiency targets. The latter prominently features the Great Recession which began in the first year of the second trading phase. We engage seriously with the concern that these policies and events may have affected regulated firms differently to matched control firms. Relevant energy policies are reviewed in Appendix B.5 with a focus on whether they have different implications for ETS and non-ETS firms, after matching. For policies that pre-dated the ETS we would expect divergent pre-trends if the policies had any differential effect on regulated firms. Any confounding effect of subsidies for renewables should lead to a differential effect on electricity generation. We do not find any evidence of this.

The Great Recession might confound estimated treatment effects in phase II of the ETS if the economic downturn or the subsequent recovery had a differential effect on firms that have characteristics associated with ETS participation. For example, the size differences in the unmatched sample, highlighted in Table 1 above, could lead us to underestimate/overstate emissions reductions if untreated small firms were more/less affected during the Great Recession than the larger, capital-intensive firms, firms that are treated. Matching on a broad set of covariates helps to reduce the potential for this issue, by minimizing differences in firm size, access to capital, scale economies and other potentially relevant differences to the degree that they are captured by the observable dimensions that we match on. To further explore the potential contribution of the Great Recession we construct geographic and industry-level measures of exposure and explore the robustness of our findings to accounting for these measures. Appendix B.4 discusses our estimation strategies and shows that our results in section 4 are robust to accounting for differential exposure to these measures of the Great Recession.

Further descriptive support for this conclusion is presented in Figure 1, which plots raw trends in CO_2 emissions, by treatment status, for matched and unmatched firms. While there is a clear fall in emissions following the Great Recession in 2008 this drop appears to happen in a near parallel way for treated and matched-control firms. In 2011 and 2012 we see more of an uptick in emissions for regulated firms in the raw data which would lead us to underestimate the effect of the EU ETS if regulated firms were differentially affected during the recovery of the Great Recession.

Figure 1: Trends in CO_2 emissions by group of firms



Notes: The figure reports average trends in (log) CO_2 emissions relative to the baseyear 2000 for various groupings of firms in our dataset: All ETS firms, ETS firms for which we can find a non ETS control firm (Matched ETS firms), those control group firms (Matched Non-ETS) and firms that are not in the ETS nor the control group (Unmatched Non-ETS).

Figure 1 also provides more general support for the parallel trends assumption prior to the introduction of the EU ETS in 2004. We see that the trajectory of emissions for matched non-ETS firms follows ETS firms closely until 2005 when permit trading begins. At this point the emissions of regulated firms sharply drop and remain lower throughout the post-treatment period. The trajectory of emissions for unmatched non-ETS firms follows less closely prior to the introduction of the policy, although even in the raw data the differences are not very substantial with deviations concentrated in the announcement period between 2001 and 2004. The closer mapping between matched non-ETS firms and ETS firms provides further support for the use of matched control firms as a counterfactual for treated firms.

In addition to the parallel trends assumption we must also assume that there are no spillovers between regulated and unregulated firms. We internalize within-firm spillovers by estimating the effects of the EU ETS at the firm-level. We cannot, however, rule out the potential for spillovers between firms. Such spillovers may take the form of emissions leaking from regulated to unregulated firms. We directly evaluate the potential for spillovers as part of our analysis, and find little evidence to suggest that they are of first-order concern in this context.

3 Data

This section details the different data used in our analysis. We compile a dataset of French manufacturing firms for each year between 1996 and 2012. This period covers several years prior to the announcement of the EU ETS, the announcement phase between 2001 and 2004, and Trading Phases I and II. The data are obtained from various sources.[11]

3.1 Energy and Emissions Data

We obtain detailed fuel use data from the Annual Survey of Industrial Energy Consumption (EACEI), a survey conducted annually by the French National Institute of Statistics and Economic Studies (INSEE).[12]

The survey provides quantities and values of energy consumed by fuel type – broadly speaking, electricity, steam, fossil fuels and biofuels.[13] Other variables available in the survey include

[11]Firm- and plant-level data from the French Statistical Office used in this paper were provided for research purposes by authorization of the *Comité du Secret Statistique*, reference E598.

[12]EACEI is the French acronym for *Enquête annuelle sur les consommations d'énergie dans l'industrie*. INSEE stands for *Institut National de la Statistique et des Études Économiques*. Until 2007, the survey was carried out by the statistical service of the Ministry of Industry, SESSI – *Service d'Études et Statistiques de l'Industrie*.

[13]Information for the following fuel types is requested from the surveyed firms: electricity (bought, auto-produced – from thermal or non-thermal process – and resold), steam, natural gas, other types of gas available on the network, coal, lignite, coke, butane, propane, heavy fuel oil, heating oil, other petroleum products, the black liquor (a byproduct of the chemical decomposition of wood for making paper pulp), wood and its by-products, special renewable fuels,

for each establishment their geographical location as well as their sectoral NCE sectoral 2-digit classification. The NCE is the designated French statistical nomenclature of activity for the study of energy production and consumption.[14]

Having reliable data on CO_2 emissions is of central importance to our study. We calculate emissions for both treated and untreated firms using the detailed energy consumption data from the EACEI in conjunction with standardized conversion factors provided by the French Environment & Energy Management Agency (ADEME).[15] Consequently, a firm will only be in our core dataset if it reports detailed energy consumption data under the EACEI, as detailed further in Section 3.7 and Appendix A.1. The sampling frame for the EACEI includes all French manufacturing establishments.[16] The response rate is close to 90 percent. This speaks to the high representativeness of the data, but it is important to note that not all establishments are covered, and that sampling rules have changed over time. In 2000, the survey covers 88% of industrial emissions in France.

Slightly different sampling weights were applied before and after 2007, but the industrial coverage remained constant, including all manufacturing except the sectors of energy production, agri-food and sawmills. Around 12,000 establishments are drawn for the sample each year and it includes (i) all industrial establishments with 20 employees or more in the most energy consuming sectors;[17] (ii) all establishments with more than ten employees in the Manufacturing of industrial gases sector; (iii) all establishments with more than 250 employees on the 31st of December of that year; (iv) a random sample of establishments with employment between 20 and 249 employees in sectors that are not energy intensive.

While the subsequent analysis is not based on the universe of French manufacturing firms, it draws on a database designed to provide a representative sample, especially of the most energy intensive firms in French manufacturing, while living up to the high standards of data collection for official statistics in France.

special non-renewable fuels.

[14]The NCE is the French acronym for the *Nomenclature d'activités économiques pour l'étude des livraisons et Consommations d'Énergie* and can be put in correspondence with the French NACE rev.2-equivalent NAF classification. https://www.insee.fr/fr/statistiques/fichier/3364874/irecoeacei16_correspondance_NCE_NAF-1.pdf

[15]ADEME is the French acronym for *Agence de l'Environnement et de la Maîtrise de l'Énergie*. EU ETS participants in France are required to use the ADEME's conversion factors when reporting their emissions.

[16]The level of survey is the establishment rather than the enterprise given that energy consuming materials, electricity and gas meters and fuel tanks are held at that level.

[17]Manufacture of bricks, tiles and construction products, in baked clay; Manufacture of cement; Manufacture of lime and plaster

3.2 Financial Data

The employment and financial variables are obtained from French fiscal data. Tax returns filed by firms with the French Ministry for the Economy and Finance are collected in the annual fiscal census of manufacturing, mining and utilities firms. Until 2007, this census was called the Unified Corporate Statistics System and the resulting dataset we exploit is the database which covers the years from 1994 to 2007.[18] For the years from 2008 until 2012, the successor system is called ESANE with the resulting dataset FARE.[19] These datasets provide general information about the firm (identifier, industry classification, head office address, total number of workers employed, age, etc.), the income statement (containing variables such as total turnover, total labor costs and value added) as well as balance sheet information (e.g. various measures of capital, debt and assets).[20] As a measure of capital, we use the value of gross fixed tangible assets, which includes machinery, equipment and buildings.

3.3 Imports Data

Firm-level data on imports for the period of 1995 to 2012 are obtained from French Customs (DGDDI).[21] The raw data are based on the customs declaration forms that firms are required to submit, and provide a comprehensive annual record of the value and quantity of exports and imports by destination, or origin, country at the eight-digit product (CN8) level. The customs dataset has been used previously in the trade literature (Eaton et al., 2011; Mayer et al., 2014). It includes the universe of trade flows from and to French firms, although reporting thresholds exist for compulsory declarations inside and outside the European Union. Outside the EU, imports are only reported if their annual total is above €1,000 or 1,000 kg. Within the EU, these thresholds vary over time and by trade flow (imports vs. exports) (Bergounhon et al., 2018). To harmonize across different thresholds, we set import levels to the highest threshold in the ETS years, i.e. €2.3 millions. Given all ETS firms were importers in the reference year 2000, we drop untreated firms that do not import any goods in that year, to increase the comparability of regulated and unregulated firms.

[18] SUSE is the French acronym for *Systeme Unifié de Statistique d'Entreprises*. FICUS stands for *FIchier Complet Unifié de SUSE*.

[19] ESANE stands for *Elaboration des Statistiques Annuelles d'Entreprises* and FARE stands for *Fichier Approché des Résultats d'ESANE*.

[20] Only observations with non-missing values for employment, value-added, emissions and capital are retained.

[21] DGDDI stands for *Direction Générale des Douanes et Droits Indirects*.

3.4 Approximating the Carbon Intensity of Imports

To measure the carbon intensity of imports, we adopt the data and approach taken by the European Commission when establishing whether a sector is at risk of carbon leakage.[22] Following this approach, the carbon intensity of a sector is measured as the percentage share of carbon permit costs in value added. Carbon permit costs are calculated as the sum of indirect and direct carbon emissions multiplied by a fixed price of €30/tCO_2. This proxy for costs is then divided by the gross value added of a sector.

For each firm and year in our dataset, we use correspondence tables between NACE rev1.1 and CN8 product codes from Eurostat's Reference and Management of Nomenclatures[23] to obtain the value of imports of goods from a given sector. Multiplying these values with the sector's carbon intensity and aggregating across sectors provides a carbon-weighted measure of a firm's imports value, reflecting the carbon intensity of its imports.

3.5 Environmental Protection Investments Data

For a subset of firms, we obtain detailed data on investments for mitigating carbon emissions and air pollution. This dataset is also collected by INSEE as part of the Annual Survey on Environmental Protection Studies and Investments (Antipol).[24] The sampling frame includes establishments from sections B, C and D of the NAF rev.2 classification, extending to some divisions of section E since 2012. Different sampling weights were applied to draw about 11,000 units. The response rate is above 80%.

The variables used here all relate to investment aimed at reducing air pollution, broadly defined. They are split between (a) investments made to "measure" air and GHG pollution, (b) "integrated" investments made in production processes and machines that are less carbon- or air pollution-intensive than alternatives, and (c) "specific" investments made solely to limit and prevent air pollution and GHG emissions, e.g. a filter. All investments are reported in thousands of Euros. In estimating (b), the "integrated" investment, respondents are asked to report the additional cost of an investment that is relevant for protecting the environment. For example, they would report the difference in the price of a new machine relative to that of an alternative that is more emissions-intensive. In addition, they report the share of total integrated environmental investments that are dedicated to air and climate pollution.

[22]Cf. in the Commission Decision 2010/2/EU, pursuant to Directive 2003/87/EC of the European Parliament and of the Council, the list of sectors and subsectors at the NACE rev1.1 four-digit level which were deemed to be exposed to a significant risk of carbon leakage (2010) OJ L 1/10.

[23]This can be accessed on: https://ec.europa.eu/eurostat/ramon

[24]In French: *Enquête sur les investissements et les dépenses courantes pour protéger l'environnement*. See Appendix C.1 for more information.

Data about investments defined as (a) were collected since 1996. However, investments defined as (b) or (c) were only included in the survey from 2001. This means that for those two categories, we can only explore changes in investment relative to 2001. Given the frequent occurrence of zero values in the dataset, we apply an inverse hyperbolic sine (IHS) transformation rather than a logarithmic transformation, $\operatorname{arcsinh} y_{it} = \ln\left(y_{it} + \sqrt{y_{it}^2 + 1}\right)$. This is approximately equal to $\log(2y_{it})$, except for very small values, and so can be interpreted in the same way as a logarithmic transformation. However, unlike the logarithmic transformation, the IHS of zero is well-defined.

3.6 EU Transaction Log Data

The European Union Transaction Log (EUTL) is the official registry of the EU ETS. It provides a list of all regulated installations, past and present.[25] A pollution right in the EU ETS is called a European Union Allowance (EUA). Each EU ETS installation has an "operator holding account" in its national registry, into which its own allowances are issued. Any individual or organization wishing to participate in the market is able to open their own "person holding account" in any of the registries. The internet portal of the EUTL makes publicly available contact details for each account, the number of allowances allocated under the "national allocation plan", and the compliance position of each installation, which is calculated as the net balance of surrendered EUAs and verified emissions. This information is provided at the annual level. We combine it with the data described above to identify regulated firms.

3.7 Analysis Sample and Descriptive Statistics

The quality of the link between entities across datasets is an important determinant of the final sample in our empirical analysis. Linking the EACEI, FICUS/FARE, trade data and Antipol is straightforward as all four datasets use unique identifiers for firms (SIREN) and plants (SIRET).[26] As described in Appendix A, linking the EACEI to FICUS/FARE and trade data leads to a sample of 4,201 firms emitting a total of 61.4 million tonnes of CO_2 in 2000, which represents 79.3% of aggregate industrial emissions from combustion of fossil fuels in France.[27] Not all firms from our main dataset are surveyed in Antipol.

[25]When the EU ETS was established in 2005, each member state created its own national registry containing allowance accounts for each plant and other market participants. These registries interlinked with the Community Independent Transaction Log (CITL), operated by the Commission, which records and checks every transaction. Since 2012, the EU ETS registry has been operated in a centralized fashion as the EUTL.

[26]SIREN is the French acronym for *Système d'Identification du Répertoire des Entreprises*. To be precise, plants in the EACEI and Antipol are identified by a SIRET (*Système d'Identification du Répertoire des Etablissements*) number. The SIREN number corresponds to the first nine digits of the SIRET number.

[27]Industrial

While the business dataset is maintained by INSEE, the French national registry of the EUTL is managed by Caisse des Dépôts. The latter institution provides a link between the permit identifier (GIDIC) from the national registry and the SIREN identifier from INSEE, allowing for the linking of the EUTL data to the business data. Out of the 4,201 firms, 252 are part of the EUETS. The main variables are summarized in Appendix Table B.1. Appendix Figure A.1 provides a visual summary of all the steps involved in the construction of the final sample from the raw data. Comparing emissions computed on the basis of the EACEI to those reported in the EUTL confirms their consistency. Appendix A.1 illustrates the 0.96 correlation between these measures. We graphically represent this relationship using a QQ plot (Figure A.2).

We reiterate that the policy is not randomly assigned across firms. On average, ETS firms are on average larger than non-ETS firms in terms of employment, value added, capital and imports (cf. Table 1). ETS firms also emit more CO_2 emissions and are more carbon intensive. These differences motivate the matching approach discussed in section 2.1, which substantially reduces baseline differences.

4 Results

4.1 Main Outcomes

Table 2 presents our main results. We estimate that, on average, regulated firms reduced emissions by 14% ($p < 0.05$) during Trading Phase I and by 16.3% ($p < 0.05$) during Trading Phase II. We fail to reject the null hypothesis that the EU ETS had no effect on the economic performance of firms, as measured by value added or the number of employees. With lower confidence than the emissions results, we estimate that regulated firms increased capital investments during Trading Phase I (8.3%, $p < 0.1$) and Trading Phase II (10.5%, $p < 0.1$). Finally, we estimate, consistent with the absence of any economic contraction, that regulated firms reduced the emissions intensity of value added during Trading Phase II (-17.4%, $p < 0.01$). We estimate a 10% reduction in the emissions intensity of output in Phase I but it is not statistically significant at conventional levels.

As discussed previously, a key assumption required for us to interpret these effects as causal is that regulated firms would have followed the same trajectory as unregulated firms in the absence of the policy. The raw data presented in Figure 1 provided initial support for this assumption. In further support of the parallel trends assumption, we do not estimate any statistically or economically meaningful differences between regulated and unregulated firms prior to the announcement or implementation of the EU ETS. Figure 2 presents a visual representation of these findings. Due to the absence of any detectable announcement effects, we present average pre-ETS effects in our results tables going forward. We continue to present pre-announcement period and announcement

Table 2: The Effect of the EU ETS on the Environmental and Economic Performance of Firms

	(1) Δ log(CO_2)	(2) Δ log(Value Added)	(3) Δ log(Emp.)	(4) Δ log(Capital)	(5) Δ log(CO_2/VA)
Pre-Announcement	0.028	0.009	0.002	-0.012	0.022
	(0.021)	(0.039)	(0.025)	(0.025)	(0.037)
Announcement Period	0.014	0.014	-0.002	0.014	0.013
	(0.025)	(0.040)	(0.019)	(0.021)	(0.034)
Trading Phase I	-0.140**	-0.050	-0.002	0.083*	-0.099
	(0.057)	(0.085)	(0.036)	(0.046)	(0.068)
Trading Phase II	-0.163**	0.097	0.046	0.105*	-0.174**
	(0.075)	(0.079)	(0.050)	(0.060)	(0.075)
Mean in 2000	82.107	55.600	684.215	132.919	3.398
Observations	2,348	2,348	2,348	2,348	2,348

Notes: This table presents estimates from OLS regressions, estimated on a matched sample. Standard errors are clustered in two ways, at the firm-level and at the matching group level. Each estimate reflects the difference between regulated firm and unregulated firm outcomes relative to the year 2000. We present estimates for four time periods: prior to the announcement of the EU ETS, during the announcement period and during Phase I and Phase II of the EU ETS. Means are reported for ETS firms in 2000. Units: CO_2 – thousands of tonnes of CO_2; Value Added – millions of Euros; Employment – full-time equivalent employees; Capital – millions of Euros; CO_2/VA units – thousands of tonnes of CO_2 per Euros of value added. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

period estimates in robustness tests.

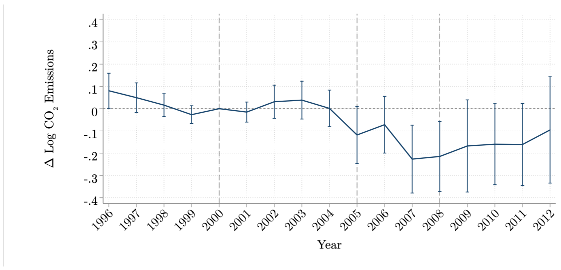
4.2 Robustness Tests

Our main results are robust to a broad range of alternative specifications and robustness tests. We summarize those findings here and refer the reader to Appendix B for the full set of results.

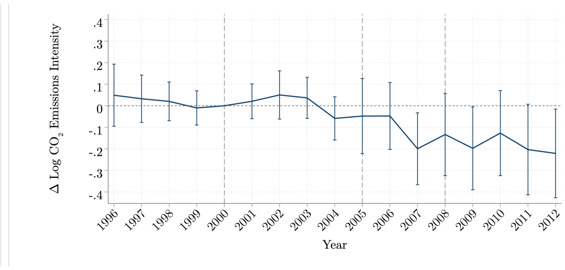
Table B.4 shows that our results are robust to including fewer matching controls (column 2), to matching without replacement (column 3), to increasing the number of nearest neighbors (columns 4-7), and to imposing common support on emissions (column 8). In Table B.5 we impose increasingly stringent caliper restrictions on the matching distance between treatment and control firms. Our results remain statistically significant until we drop more than 10% of the treated firms with the largest difference; however, even when we drop 25% of treated firms the results remain qualitatively robust.

More substantive concerns relate to the potential for overlapping policies and events that could differentially affect regulated firms, confounding our interpretation. The absence of any effects on economic performance helps to mitigate the concern that the estimated effects might be confounded by differential reactions to the Great Recession between treated and control groups. If this was the case, we would expect to see differential responses in economic outcomes as well, not just

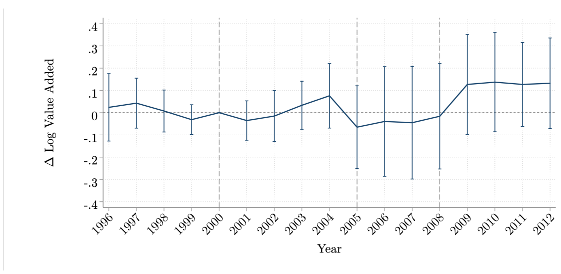
Figure 2: The Effect of the EU Emissions Trading Scheme on the Environmental and Economic Performance of Firms



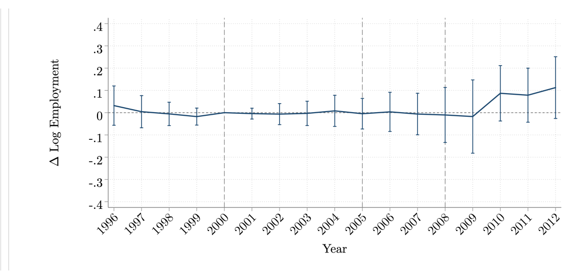
(a) CO_2 Emissions



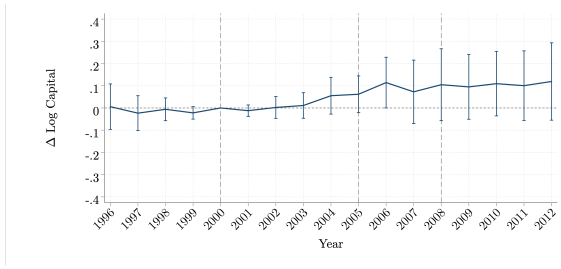
(b) Carbon Intensity



(c) Value Added



(d) Employment



(e) Capital Stock

Notes: These figures presents estimates from OLS regressions, estimated on a matched sample. Standard errors are clustered in two ways, at the firm-level and at the matching group level. All variables are in logs and normalized at the year 2000. Vertical red lines relate to the different phases of the EU ETS. The EU ETS was announced in 2000 and the first phase began in 2005. Phase II of the EU ETS began in 2008. Standard errors are clustered twoways at the firm and match group level.

in environmental outcomes. It is possible that the Great Recession had a differential negative effect on non-ETS firms offsetting any negative effects of the ETS on regulated firms. In this case our estimated reductions in emissions would represent a lower bound on the effect of the ETS during the Phase II trading period.

A more direct way of assessing confounding effects of the Great Recession is by directly controlling for its effects in the regression. In Appendix B.4, we show that this is possible in a straightforward modification to the estimation framework. The intuition behind our approach is that if the recession shocks of treated and matched controls are observed and included in the regression they can no longer confound the estimated ETS coefficient. While firm-specific recession shocks are unobserved, we can proxy for them using suitable spatial and sectoral measures of unemployment changes between 2008 and 2009. We include these variables, separately for treated and control firms, when re-estimating our main results. Table B.6 shows that the inclusion of these variables has no effect on our Phase I treatment effect as should be expected. In Phase II the coefficient is slightly attenuated from -16.3% in our main results to -14.5%. These results lend further credibility to our identifying assumption that the Great Recession did not have differential effects on ETS firms.

A second concern is that other policies may confound the interpretation of our estimates. The EU ETS was not implemented in isolation but in a policy context marked by the commitment by the EU to reduce emissions by signing the Kyoto Protocol in 1997. Under the EU Burden-Sharing Agreement, France was called upon to implement policies in addition to the EU ETS to contribute its fair share to the EU-wide abatement target. Such overlapping policies included energy taxes, subsidies for renewable energy, and the promotion of energy efficiency.

Appendix B.5 provides more detail on these policies and explains how differences in the timing of when policies were introduced compared to the EU ETS can be exploited to draw inferences about their empirical relevance in contributing to our results. For example, we show that feed-in tariffs for electricity from renewable and small co-generation plants did not affect firms differentially. We conclude that overlapping energy and climate policies in France were unlikely to drive the sizable and robust emissions reductions we estimate in Table 2.

Beyond the Great Recession and introduction of other energy policies, our study is set during a time where France is going through a broader process of de-industrialization. Firm exit may have contributed to secular declines in CO_2 emissions. Due to data limitations, we are unable to directly evaluate firm exit. We therefore abstract from firm exit and analyze a balanced sample of firms observed in each one of the four periods. To the degree that the EU ETS induced firms to exit our sample before Phase II, our estimated emissions reductions represent a lower bound of the total effect of the EU ETS on industrial emissions. In Appendix B.6, however, we provide evidence that there is no differential attrition by ETS firms when constructing our balanced sample.

5 Mechanisms

Our findings indicate that the EU ETS induced regulated firms to reduce emissions with no detectable effects on economic performance. In this section, we investigate the mechanisms that drive these results.

5.1 Leakage

While we estimate that the ETS is associated with reductions in the emissions of regulated firms, what matters for climate change mitigation is whether the ETS reduced global emissions. Regulated firms may have cut emissions by outsourcing carbon-intensive elements of the value chain to unregulated firms or markets. Carbon leakage threatens the efficacy of the ETS by limiting, or even reversing, the effect on global emissions. For example, if the emissions intensity of production in upstream facilities is higher than in regulated facilities global emissions could increase as a consequence of the policy.

To assess the efficacy of the EU ETS as a climate policy instrument, it is therefore important to understand whether the CO_2 abatement we have estimated represents a global reduction in emissions.

Carbon leakage could occur through multiple channels. Three of them are particularly relevant in the context of our study. The first channel is via the supply chain, i.e., by out-sourcing more intermediate products from unregulated firms. Such a strategy could save on compliance costs, particularly if applied to the most carbon-intensive steps of the value chain. But it would inevitably reduce the firm's value added, defined as "revenue minus material inputs", where material inputs are sourced both domestically and through international trade. We do not estimate any reduction in value added. Moreover, regression results reported in columns 1 and 2 of Table 3 show that there is no statistically significant association between the EU ETS and the importing behavior of regulated firms; however, the coefficient on total imports in Phase II would imply a 4.5% increase in imports if taken at face value.

We bound the potential contribution of imports to our reduction in emissions by combining a naive estimate of the elasticity between emissions intensity and imports, -0.097 with an upper bound of the increase in total imports (18.6%)[28] We calculate that increased imports in Phase II could account for at most a 1.8% reduction in emissions intensity, accounting for at most 10% of the estimate in Trading Phase II. Our collective findings on value added and imports, alongside

[28] The elasticity between emissions intensity and imports is estimated using a bivariate OLS regression of the form log(CO_2/Value Added$_{it}$) = α + β log(total imports$_{it}$) + ϵ_{it}. We estimate the elasticity using all firms in years prior to the EU ETS. The inclusion of firm and sector-year fixed effects attenuates the estimate to -0.022. The upper bound estimate for the increase in total imports is calculated as, $4.5\% + 1.96 \times 7.2\%$.

back-of-the-envelope calculations, provide little evidence to indicate that out-sourcing is likely to be a major driver of our estimated emissions reductions.

The second potential channel of carbon leakage is via the product market. Because carbon pricing increases production costs at regulated firms, market forces might shift production to unregulated firms within France or abroad. If this process was driving the negative effect we estimate for emissions, we would expect to also see negative effects of the EU ETS on at least one of the economic variables such as value added, employment or investment. Instead, however, we estimate insignificant effects on employment and value added, and positive effects on capital investment. Apart from mitigating concerns about leakage, this result is useful as a an indirect test of whether treatment spillovers, which could pose a threat to our identification strategy, are empirically relevant in this context. Product-market leakage is isomorphic to a treatment spillover between regulated and unregulated firms which reallocates market share from regulated to unregulated firms. This would violate SUTVA and lead to an overstatement of the treatment effect as emissions fall at regulated firms and increase at unregulated firms, in lock-step with production. Yet again, the same effect should be observed for other variables relating to the scale of production. We find no evidence that this is the case. We only estimate reductions in emissions.

A third possible channel of leakage arises if firms operating multiple facilities reallocate production from regulated to unregulated ones. We internalize within-firm spillovers by estimating the effects of the EU ETS at the firm-level. Consequently, within-firm leakage cannot explain estimated emissions reductions at the firm-level. Our estimates are net of any within-firm leakage.[29]

5.2 Abatement Channels

The absence of evidence on carbon leakage, combined with the estimated reduction in the carbon intensity of value added, supports the view that emission reductions arose from improvements to the emissions intensity of production. Such improvements can be achieved by switching to less polluting fuels or by investing in technology that is more efficient (or from investments in technology that allows fuel switching). Our data allow us to explore these different channels of abatement.

[29] Of all regulated firms, 40% have unregulated CO_2 emissions. In Table A.2 we document that the share of total emissions that are regulated is very high in all sectors. In the Pharmaceuticals sector, which has the lowest average share of total emissions that are regulated 68.22% of emissions are regulated. On average, 88% of emissions in regulated firms are covered by the ETS.

Table 3: Exploring Mechanisms

	Import Responses		Fuel-Mix Responses		Pollution-Control Investments			Productivity
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Δ log(Imports) Total	Δ log(Imports) CO_2 intensive	Δ Gas Share in CO_2	Δ Electricity Bought Share	Δ asinh^{-1} (Measurement)	Δ asinh^{-1} (Integrated)	Δ asinh^{-1} (Specific)	Δ log (TFPR)
Pre-ETS	-0.046	-0.050	0.000	0.000	0.232	0.061	-0.058	-0.011
	(0.033)	(0.062)	(0.004)	(0.002)	(0.203)	(0.216)	(0.262)	(0.019)
Trading Phase I	0.019	0.027	-0.009	-0.004	0.299	0.996***	0.413	-0.026
	(0.060)	(0.118)	(0.017)	(0.006)	(0.281)	(0.285)	(0.251)	(0.051)
Trading Phase II	0.045	-0.026	-0.018	-0.003	-0.073	0.844**	0.325*	0.049
	(0.072)	(0.134)	(0.029)	(0.007)	(0.259)	(0.353)	(0.173)	(0.054)
Mean in 2000	156.847	0.742	0.708	0.268	12.964	12.497	12.624	5.021
Observations	2,298	2,267	2,348	2,348	1,548	1,061	1,061	2,270

Notes: These estimates are the result of OLS regressions, estimated on a matched sample. Standard errors are clustered twoways: at the firm level and the matching group level. Each estimate reflects the difference between regulated firm and unregulated firm outcomes prior to implementation of the ETS and during Phase I and Phase II of the EU ETS. Each coefficient represents the difference relative to the year 2000. Means are reported for ETS firms in 2000 (2001 for Columns 6 and 7). Units: total imports and CO_2 Intensive Imports are measured in millions of Euros; Gas Share of Emissions and Electricity Share of Total Energy Consumed are shares between 0 and 1; investment into the measurement of emissions is measured in thousands of Euros; investment in integrated investments made in production processes and machines that are less carbon- or air pollution-intensive than alternative is measured in thousands of Euros; investment into specific, 'end-of-pipe' measures to reduce emissions is measured in thousands of Euros.Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

In column 3 of Table 3 we estimate that there was no change in the share of natural gas in total CO_2 emission. Another possible fuel-switching channel is that regulated firms used more electric energy in the production process. The principal mechanism for this is by procuring more electricity from the grid. In column 4 we estimate that there was no change in the electricity share of total energy use in the firm. Firms could also generate more electricity on site, but this is quite rare among the firms in our sample and would lead to higher direct emissions, contrary to what we find. In Table B.7 we estimate no extensive-margin adjustments to on-site generation from conventional and renewable sources. In sum, the results indicate that fuel switching to natural gas or electricity cannot explain the estimated CO_2 abatement at regulated firms. An implication for climate change mitigation is that CO_2 abatement by regulated manufacturing firms did not lead to increased emissions in the electricity sector.[30]

This leaves technology adoption as a possible mechanism behind the reductions in carbon emissions and emissions intensity of regulated firms. The positive treatment effect on capital stock is suggestive, but not conclusive, evidence that regulated firms invested in reducing the emissions intensity of production. Columns 5-7 in Table 3 provide further evidence in support of this hypothesis using data on pollution control investments for a sub-sample of firms in our sample. Specifically, we estimate that regulated firms significantly increased their investments in integrated production technologies that reduce air and climate change related pollution emissions, such as more efficient boilers, during Trading Phases I and II (column 6). In column 5, we do not estimate any differential impacts on investments into the measurement of emissions (not needed for CO_2 given the ease of input-based accounting). We estimate smaller marginally significant investments into specific, 'end-of-pipe' measures to reduce emissions (not yet available for CO_2 at a commercial scale). A caveat with this analysis is that, unfortunately, data for integrated and specific investments were only collected from 2001 onward. Consequently, we are unable to investigate whether trends in those outcomes are parallel during the pre-announcement period. We do not estimate any differential effect prior to the introduction of the ETS for these variables and for measurement investments we do not estimate any differential effect in the pre-announcement phase.

A review of the metadata of the Antipol survey (see Section C.1) provides additional details about the survey but does not provide a lot of detail about the types of investments that firms make. To provide further insight we take advantage of as yet unused data from interviews conducted in 2009 with the managers of 140 French manufacturing firms, 92 of which participate in the EU ETS (see Martin et al., 2014b, for details about the data collection). In Appendix C.2 we explore responses to interview questions pertaining to measures that were implemented at the production

[30]It is likely that buying electricity would not lead to an increase in global emissions because 79% of the electricity generated in France in 2012 was carbon neutral, and the remaining 21% – including the marginal generator– is likely to have been produced by power plants under the EU ETS cap.

site to reduce CO_2 emissions. Managers were asked "Can you tell me what measures you have adopted in order to reduce GHG emissions (or energy consumption) on this site? Have you bought any new equipment, or have you changed the way you produce?" We document that more than 30% of managers report adopting optimization processes targeted at heating, waste heat recovery, industry-specific processes or machinery, and lighting.[31]

Firms participating in the EU ETS were more likely to report making investments to optimize the use of process heat[32] and to optimize processes specific to their industry, than non-ETS firms. We note that these correlations are descriptive and do not necessarily represent causal relationships. Nevertheless, in combination with our main results, these qualitative insights provide supporting evidence for the hypothesis that firms invested in new processes to reduce emissions.

Collectively, our findings suggest that the principal mechanism underlying the estimated emissions reductions is that treated firms reduced the carbon intensity of production by upgrading their capital stock.

5.3 Productivity

What remains unresolved is that firms reduced emissions without any detectable contraction in economic activity despite the fact that carbon pricing increased input costs. One hypothesis is that the ETS induced firms to make investments that increased productivity offsetting any costs to the firm. However, the conditions under which such an interpretation can be rationalized are unclear. To explore this conjecture, we present a model of firm production which guides our evaluation. We use the structure of this model to estimate revenue based Total Factor Productivity (TFPR) and evaluate the effect of the EU ETS on measured TFPR.[33] We estimate that, on average, the EU ETS had a positive but statistically insignificant effect on measured TFPR. We explore the implications of this finding first through the lens of a parsimonious baseline model. In contrast to our empirical findings, this baseline model predicts contractions in economic activity and weakly decreasing effects on productivity under the EU ETS. Next, we present a simple extension to the model incorporating the possibility for high substitutability between certain types of capital and polluting energy inputs, as well as the potential for inattention or learning-from-investment delivers under-investment in clean capital prior to the introduction of costly regulations. This extension rationalizes all of our empirical findings, delivering the possibility of weakly increasing effects on value added, employment, total capital, and productivity. Additional analysis guided by

[31]More than 15% of managers reported switching to natural gas, modernizing the compressed air system, innovating in the production processes, upgrading the energy management system, but also improving waste management and running employee awareness campaigns to reduce energy use.

[32]As highlighted by Ammar et al. (2012); Barma et al. (2017); Chowdhury et al. (2018), there is a sizable potential for waste recovery in the industrial sector. We thank an anonymous referee for pointing us to those studies.

[33]We use a simplified version of the approach proposed in Forlani et al. (2016) and used in Aghion et al. (2023)

the predictions of the model provide further support for this interpretation. The remainder of this section provides more details on each step of this investigation.

5.3.1 Model Setup

Consider a firm that uses capital K, energy services E, intermediate inputs M and labor L, to produce output Q.[34] Using energy services gives rise to CO_2 emissions when those services are produced with fossil fuels. We assume a Cobb-Douglas production function

$$Q = AE^{\alpha_E}K^{\alpha_K}M^{\alpha_M}L^{\alpha_L} \tag{3}$$

with returns-to-scale parameter $\gamma \equiv \alpha_K + \alpha_E + \alpha_M + \alpha_L$. The firm maximizes profits subject to an inverse isoelastic demand function[35]

$$P = \Lambda^{\frac{1}{\mu}}Q^{\frac{1-\mu}{\mu}} \tag{4}$$

where μ is the markup of prices over marginal costs and Λ is a demand shifter. Taking input prices, W_X, as given, a monopolistic firm's profit maximisation problem becomes

$$V = \max{}_{E,K,M,L}\left\{\Lambda^{\frac{1}{\mu}}Q^{\frac{1}{\mu}} - \sum_{X\in\{E,K,M,L\}} W_X X\right\}$$

This leads to the following first-order conditions (FOC),

$$X = \frac{\alpha_X}{\mu W_X}Q^{\frac{1}{\mu}}\Lambda^{\frac{1}{\mu}} \tag{5}$$

for $X \in \{E, K, M, L\}$, where we assume that all input factors are flexible. Using the production function, we solve for optimal output

$$Q^* = \left[A\prod_{X\in\{E,K,M,L\}}\left(\frac{\alpha_X}{W_X}\right)^{\alpha_X}\frac{\Lambda^{\frac{\gamma}{\mu}}}{\mu^{\frac{\gamma}{\mu}}}\right]^{\frac{\mu}{\mu-\gamma}}. \tag{6}$$

[34]Following the literature, we use the term energy services to draw a distinction between the usage firms or households derive commonly from specific fuels, e.g. heating, and units of the fuel, e.g. tonnes of coal. We abstract from the fact that some energy services are derived from fuels that are not directly regulated at the firm level (electricity). We also do not explicitly model that some fossil fuels, e.g natural gas in the chemical industry, are used as direct inputs in the production process rather than to derive energy services.

[35]This demand function would follow from a CES utility function in a monopolistic competition setting.

5.3.2 Measuring total factor productivity (TFP)

Like most studies on firm-level productivity we do not observe physical output in our data. Instead we observe revenue. Given the log-linear demand model function (4) we can write revenue as:

$$R = \Lambda^{\frac{1}{\mu}} Q^{\frac{1}{\mu}}. \tag{7}$$

Under our assumptions about the production function this can be restated as

$$R = \Lambda^{\frac{1}{\mu}} A^{\frac{1}{\mu}} \prod_X X^{\frac{\alpha_X}{\mu}}. \tag{8}$$

Taking natural logarithms and using lower-case letters to denote logged variables yields

$$r = \frac{1}{\mu}(\lambda + a) + \sum_x \frac{\alpha_X}{\mu} x \tag{9}$$

From the FOC, we get the expression

$$X = \frac{1}{\mu} \frac{\alpha_X}{W_X} R \qquad \forall X$$

which we can rearrange to get

$$s_X \equiv \frac{W_X X}{R} = \frac{\alpha_X}{\mu} \tag{10}$$

Substituting this into equation (9) yields

$$r = \frac{1}{\mu}(a + \lambda) + \sum_{X \neq K} s_x x + \left(\frac{\gamma}{\mu} - \sum_{X \neq K} \frac{\alpha_x}{\mu} \right) k \tag{11}$$

where we have used the definition of the scale parameter $\gamma = \sum_X \alpha_X$. Rearranging terms leaves us with the following expression which clarifies the notion of revenue productivity, as a composite of the technical efficiency a and the demand shifter λ:

$$\frac{1}{\mu}(a + \lambda) = r - \sum_{x \in \{e,l,m\}} s_x (x - k) - \frac{\gamma}{\mu} k \tag{12}$$

We examine two measures of TFPR that build on this formula.

Index-number based TFP residual Consider

$$\tilde{\omega}_{it} = r_{it} - \sum_{x \in \{e,l,m\}} \breve{s}_x \left(x_{it} - k_{it}\right) - k_{it} \tag{13}$$

where $\breve{s}_x$ are the median expenditure shares for factors energy (E), intermediates (M) and labour (L). Subscript i indexes a particular firm and t a time period.

We use the median factor shares observed in the cross section of firms to reduce the impact of outliers. If firms flexibly adjust labor, intermediates, and energy (but not necessarily capital), then the productivity index (13) represents a composite of the production function and demand shift parameters which can be interpreted as revenue productivity, $\tilde{\omega}_{it} \approx a_{it} + \lambda_{it}$, provided that the returns-to-scale and markup parameters γ and μ are close to one.

Estimation-based TFP residual If firms have non-constant returns-to-scale γ and/or markups $\mu > 1$ then the above approach is unlikely to provide a consistent estimate of revenue productivity. In this case we need an estimate of $\frac{\gamma}{\mu}$ to recover an index $\omega_{it} = \frac{1}{\mu}(a_{it} + \lambda_{it})$ of revenue productivity. This requires timing assumptions for ω_{it} and k_{it}. We assume an AR(1) process for ω_{it} ,

$$\omega_{it} = \rho \omega_{it-1} + \eta_{it} \tag{14}$$

and that k_{it} is pre-determined in period t.[36] Under these assumptions we write:

$$\Theta_{it} - \frac{\gamma}{\mu} k_{it} = \rho \left(\Theta_{it-1} - \frac{\gamma}{\mu} k_{it-1} \right) + \eta_{it}$$

where $\Theta_{it} = r_{it} - \sum_{x \in \{e,l,m\}} \tilde{s}_x \left(x_{it} - k_{it}\right)$. Rearranging yields a regression equation

$$\Theta_{it} = \frac{\gamma}{\mu} k_{it} + \rho \frac{\gamma}{\mu} k_{it-1} + \rho \Theta_{it-1} + \eta_{it}. \tag{15}$$

that we estimated by OLS and compute revenue productivity as

$$\hat{\omega}_{it} = \Theta_{it} - \widehat{\left(\frac{\gamma}{\mu}\right)} k_{it} \tag{16}$$

In our empirical analysis we focus on this measure of TFPR because it is less restrictive. Results are robust to using the index-based measure $\tilde{\omega}_{it}$.

[36] This is a simplified version of approaches further discussed in Forlani et al. (2016) and Aghion et al. (2023) and in line with similar approaches in the literatures; see, e.g., Klette & Griliches (1996); Olley & Pakes (1996); De Loecker & Warzynski (2012); Ackerberg et al. (2015).

5.3.3 Productivity impacts of the EU ETS

This subsection shows that the predictions of the above model match some but, crucially, not all of our empirical findings. This provides the motivation for extensions of the standard model which help to fully rationalize our empirical results, and which we introduce in the next subsection.

In line with the literature (Baumol & Oates, 1988), we consider that the main effect of the EU ETS is to increase the price of energy services. If, as we have assumed above, profit-maximizing firms take factor costs as given, an increase in the price of carbon has no effect on a TFPR measure based on equation 12. As shown in Appendix Section E, TFPR remains equal to $\omega_{it} = \frac{1}{\mu}(a_{it} + \lambda_{it})$.

Contrary to this, Greenstone et al. (2012) model that environmental regulation reduces TFP, based on the notion that firms divert some exogenous share of their observed inputs to uses that do not contribute to observed output but that are needed to comply with the regulation. In the case of the EU ETS, such unproductive labor inputs may include employees that are in charge of measuring emissions, managing the permit holdings and communicating with the regulator. In the context of our model this would imply that the amount of effective labor is a fraction ν of total employment, i.e.,

$$Q_{ETS} = AE^{\alpha_E} K^{\alpha_K} M^{\alpha_M} (\nu L)^{\alpha_L} = \nu^{\alpha_L} Q. \tag{17}$$

The first order conditions are unchanged and therefore $Q^*_{ETS} = \nu^{\alpha_L} Q^*$. The effect of the EU ETS on TFP (ω) becomes

$$\Delta\omega = \omega_{ETS} - \omega = \frac{\partial \omega}{\partial q} \frac{\partial q}{\partial \ln \nu} \Delta\nu = \left(1 - \frac{\gamma}{\mu}\right) \frac{1}{\mu} \alpha_L \ln \nu$$

which is negative since $\nu < 1$.

In column 8 of Table 3 we estimate that the EU ETS has no effect on measured TFPR, which is more consistent with our baseline model than the extension by Greenstone et al. (2012). However, we have other results that do not match the predictions of our baseline model. The model predicts negative effects on value added, employment, and capital.

In our setting value added is equal to

$$VA = R - W_E E - W_M M \tag{18}$$

Hence,

$$\frac{\partial VA}{\partial W_E} = \frac{\partial R}{\partial W_E} - E - W_E \frac{\partial E}{\partial W_E} - W_M \frac{\partial M}{\partial W_M}$$

Note from (5) that $\frac{\partial E}{\partial W_E} = -\frac{E}{W_E} + \frac{\alpha_E}{\mu W_E} \frac{\partial R}{\partial W_E}$ and $\frac{\partial M}{\partial W_E} = \frac{\alpha_M}{\mu W_E} \frac{\partial R}{\partial W_E}$ so that

$$\frac{\partial VA}{\partial W_E} = \frac{\partial R}{\partial W_E} \left(1 - \frac{\alpha_E}{\mu}\right) = \frac{1}{\mu} \frac{\partial Q}{\partial W_E} \left(1 - \frac{\alpha_E}{\mu} - \frac{\alpha_M}{\mu}\right) < 0$$

as $\frac{\partial Q}{\partial W_E} < 0$ and $\alpha_E + \alpha_M$. A higher cost from carbon pricing implies that firms should reduce their output and as a consequence factor demand for all inputs. Ceteris paribus, value added, capital, and employment should all fall. Instead, we estimate a significant increase in capital and positive (but statistically insignificant) effects of the ETS on value added and employment. To rationalize those results we need to augment the baseline model.

5.3.4 A model with substitutability and biased beliefs

Our augmented model has two additional features. First, it accommodates the observed increases in investment by allowing for the possibility that some types of capital can be substituted for dirty energy. We accomplish this by introducing clean capital C that is a perfect substitute for energy services E and hence saves fossil fuel. Firms consume energy services according to

$$E = F + \kappa C \tag{19}$$

where $\kappa > 1$ captures the relative efficiency of units of clean capital compared to units of fossil fuel. Let $\sigma \in (0, 1)$ denote the maximum share of energy services that can be provided from clean technologies:

$$\kappa C < \sigma E \tag{20}$$

These assumptions allow high substitutability between F and C while also ensuring that E is not entirely provided by C.[37] If

$$W_F > \frac{W_C}{\kappa}$$

where W_C is the user cost of clean capital, it is cost minimizing for firms to use clean energy capital according to

$$C = \frac{\sigma}{\kappa} E$$

and fossil fuels according to

$$F = (1 - \sigma) E.$$

Modified in this way, the model rationalizes increases in C as well as total capital $C + K$ provided that $W_F < \frac{W_C}{\kappa}$ prior to the introduction of the policy. The model cannot, however, explain the absence of contractions in value added or employment, which creates the need for an additional feature.

The second modification of the baseline model concerns the firm's beliefs regarding the performance of clean capital C. We assume that firms that have not yet invested in C may be imperfectly

[37] A more realistic yet notationally more cumbersome case would be to allow for limited substitutability between the two factors.

informed or inattentive and underestimate the performance of C by ρ percent.[38] These firms consider the production of energy services to be governed by the function

$$E = F + (1-\rho)\kappa C \qquad \rho \in (0,1] \tag{21}$$

such that no investment in C occurs while $W_F < \frac{W_C}{\kappa(1-\rho)}$. In turn, if the emission price P_{ETS} (scaled appropriately to the carbon content of fossil fuel) is high enough, $W_F + P_{ETS} > \frac{W_C}{\kappa(1-\rho)}$ inattentive firms may invest in C following the introduction of the policy, and update their beliefs about the cost-savings associated with C. Firms with $C > 0$ (or $W_F + P_{ETS} > \frac{W_C}{\kappa(1-\rho)}$) will use energy according to the first-order condition

$$F = (1-\sigma)\,\frac{\alpha_E Q^{\frac{1}{\mu}}}{\mu W_E}\Lambda^{\frac{1}{\mu}}$$

where the unit cost of energy services becomes

$$W_E = (W_F + P_{ETS})\,(1-\sigma) + \sigma\frac{W_C}{\kappa}$$

and demand for clean capital satisfies the equation

$$C = \frac{\sigma}{\kappa}\frac{\alpha_E Q^{\frac{1}{\mu}}}{\mu W_E}\Lambda^{\frac{1}{\mu}}.$$

From equation (6) we see that output would increase if

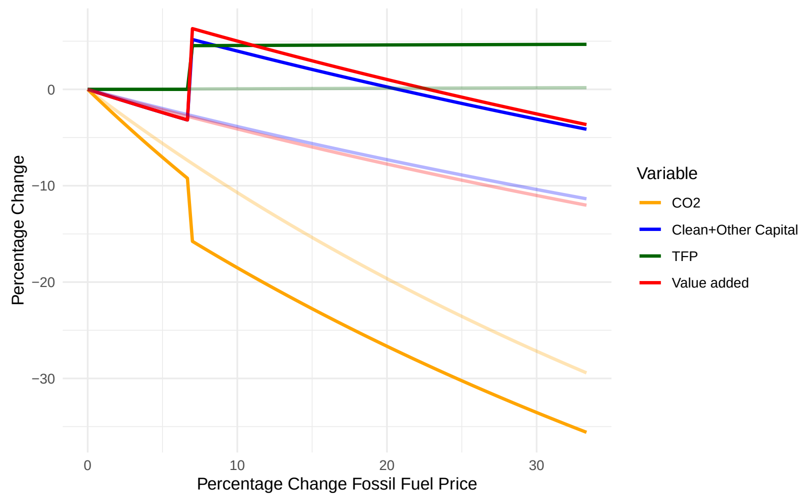
$$(W_F + P_{ETS})\,(1-\sigma) + \frac{\sigma}{\kappa}W_C < W_F$$

which may happen when σ is close enough to 1, W_C is sufficiently smaller than W_F, P_{ETS} is not too big, or κ is sufficiently high. Therefore, the notion that firms may be inattentive to the performance of clean technology (a market failure in addition to the externalities associated with carbon pollution) can rationalize positive output and employment effects in response to environmental regulation.

While the bias parameter ρ is not directly observable to us, we conjecture that it correlates with observable firm characteristics. In particular, firms with low productivity or high energy intensity are more likely to be less informed or less attentive about the returns to clean technology investments. These firms would have high values of ρ, and we would thus expect them to respond to the carbon price P_{ETS} more strongly in terms of emissions reductions, investment, and possibly

[38] This idea is motivated by the framing and discussion of imperfect information and inattention in Allcott & Greenstone (2012).

Figure 3: Simulated Effects of the ETS on Firm Behavior when Firms are Inattentive



Notes: The figure depicts the effect of carbon pricing on inattentive firms for different variables (lines with solid colors). The vertical axis shows the percentage changes in different variables as a function of percentage increases in fossil fuel prices due to carbon pricing (horizontal axis). The lines with translucent colors show the effect on the same variables for firms without biased beliefs, i.e., $\rho = 0$. For a sufficiently high increase in fossil fuel prices, we see a dramatic reduction in CO_2 alongside increases in TFP, value added and total capital (consisting of conventional and clean capital). Parameters used for the Figure: $\alpha_K = 0.8$, $\alpha_E = 0.4$, $\sigma = 0.3$, $\rho = 40\%$, $\kappa = 1.3$, $\mu = 2$. Alternative parameters can be explored in our accompanying web app found here.

value added or TFP. Figure 3 visualizes this using numerical simulations from our model. CO_2 emissions drop for any increase in carbon pricing. There is an additional drop when inattentive firms are pushed over the adoption threshold. Alongside this drop we see an increase in the growth rate of value added and investment that can be net positive as long as the carbon price is not too high.

In Table 4 we provide empirical support for these predictions, by exploring heterogeneity in our main results between firms that we conjecture are more likely to be inattentive (high ρ) and firms that are less likely to be inattentive (low ρ). We classify firms as "attentive" if, in the base year 2000, their TFPR is above and their energy intensity is below their respective industry medians.[39] In this way we classify 73% of ETS firms in our sample as inattentive.

Consistent with the predictions of the model, we estimate large and significant reductions in emissions, increases in value added and increases in total capital for inattentive, "high ρ" firms. We also estimate positive coefficients on employment and measured TFPR in Phase II but these effects are statistically insignificant at conventional levels. By contrast, for attentive, "low ρ"

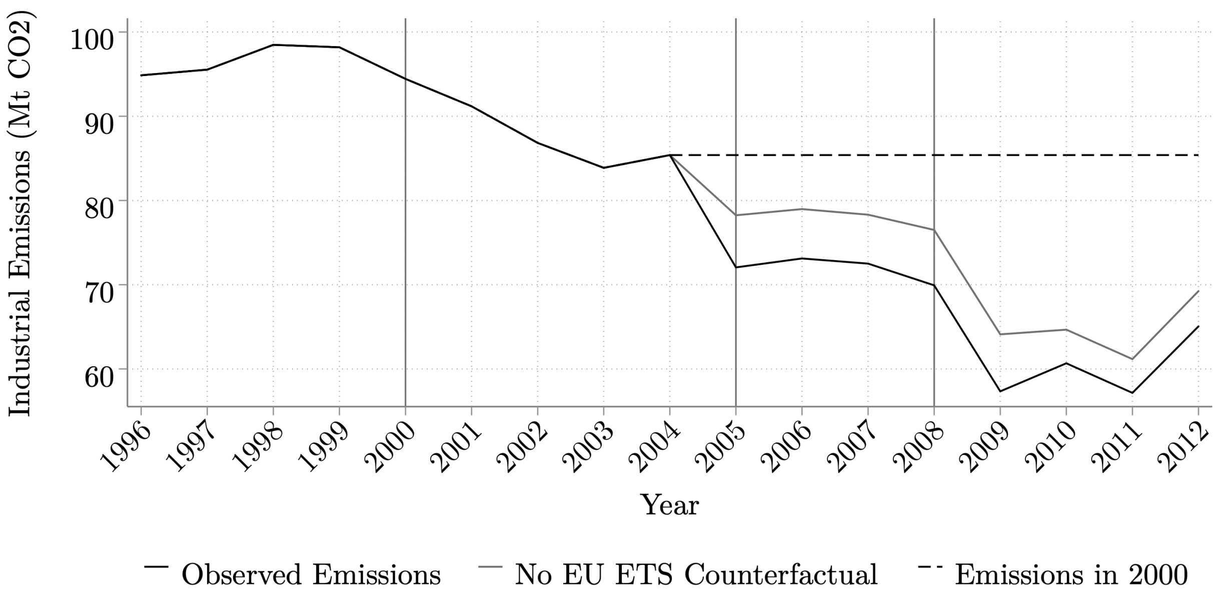
[39] We conjectured that firms with low productivity (TFPR) and high energy intensity are inattentive and firms with high TFPR and low energy intensity are definitely attentive and well informed about energy and carbon saving technologies. For firms with either high TFPR and high energy intensity or low TFPR and low energy intensity we did not have strong priors. However, in our data we find that their responses to the policy are similar to those of inattentive firms. Hence our grouping in the results in Table 4. More details about this can be found in Appendix D.

Table 4: Heterogeneity in the Effect of the EU ETS on the Environmental and Economic Performance of Firms by Productivity/Energy Intensity

	(1)	(2)	(3)	(4)	(5)	(6)
	Δ log(CO_2)	Δ log(VA)	Δ log(Emp.)	Δ log(Capital)	Δ log(CO_2/VA)	Δ log(TFPR)
A. "Attentive" Firms						
Pre-ETS	0.012	-0.021	-0.008	0.017	0.012	-0.031
	(0.026)	(0.072)	(0.022)	(0.021)	(0.053)	(0.038)
Trading Phase I	-0.046	-0.191	-0.051	0.075	0.121	-0.065
	(0.100)	(0.144)	(0.060)	(0.078)	(0.116)	(0.085)
Trading Phase II	-0.037	-0.118	-0.066	0.057	0.074	-0.005
	(0.128)	(0.152)	(0.090)	(0.088)	(0.145)	(0.112)
B. "Inattentive" Firms						
Pre-ETS	0.024	0.023	0.005	-0.006	0.021	-0.003
	(0.019)	(0.032)	(0.018)	(0.019)	(0.029)	(0.020)
Trading Phase I	-0.174***	0.011	0.025	0.095*	-0.186**	-0.008
	(0.063)	(0.094)	(0.045)	(0.053)	(0.073)	(0.058)
Trading Phase II	-0.190**	0.192**	0.097	0.134*	-0.255***	0.069
	(0.086)	(0.090)	(0.059)	(0.074)	(0.084)	(0.060)
Observations	2,297	2,297	2,297	2,297	2,297	2,270

Notes: These estimates are the result of OLS regressions estimated on a matched sample. Standard errors are clustered in two ways at the firm-level and at the matching group level. Each estimate reflects the difference between regulated firm and unregulated firm outcomes relative to the year 2000. We present estimates for three time periods: prior to the implementation of the EU ETS, during Phase I and during Phase II of the EU ETS. Coefficients reported in panels A and B are obtained in a single regression for each column, with treatment interactions for "attentive" firms, i.e. those with above-median TFPR and below-median energy intensity, relative to their industry, in the base year 2000. Firms not belonging to this group are labeled "inattentive". Panel A reports estimates for "Attentive" firms. Panel B reports estimate for "Inattentive" firms. Units: CO_2 – thousands of tonnes of CO_2; Value Added (VA) – millions of Euros; Employment – full-time equivalent employees; Capital – millions of Euros; CO_2/VA units – thousands of tonnes of CO_2 per Euros of value added. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

Figure 4: The Effect of the EU ETS on Aggregate Emissions Reductions



Notes: The black line presents the aggregate time series for industrial emissions in France, measured in millions of tonnes of CO_2. The dark gray line represents counterfactual emissions in the absence of the EU ETS, using our difference-in-differences estimates and assuming that 75% of industrial emissions are regulated. The dashed black line represents the level of emissions in 2000 as a benchmark.Source: Authors calculations based on French microdata and Eurostat data.

firms we estimate statistically insignificant and small reductions in emissions, value added, and employment. The point estimates for TFPR are also negative but statistically indistinguishable from zero.

6 Aggregate Carbon Savings

We combine our estimates with the aggregated microdata on CO_2 emissions to gauge the potential contribution of the EU ETS in driving aggregate emission reductions since 2005. Details on the calculations made below can be found in Appendix E.

The black line in Figure 4 depicts observed of aggregate industrial CO_2 emissions in France between 1996 and 2012 constructed using our microdata. We observe that aggregate emissions have been falling over time, and that the decline has been steeper in recent years.

We see a substantial aggregate drop in emissions starting in 2005 at the start of the ETS and again in 2008 at the start of phase II. The dashed line plots emissions in 2004 as a benchmark for these drops. These findings are consistent with our empirical evidence, but the question remains, how much the ETS contributed to these aggregate reductions?

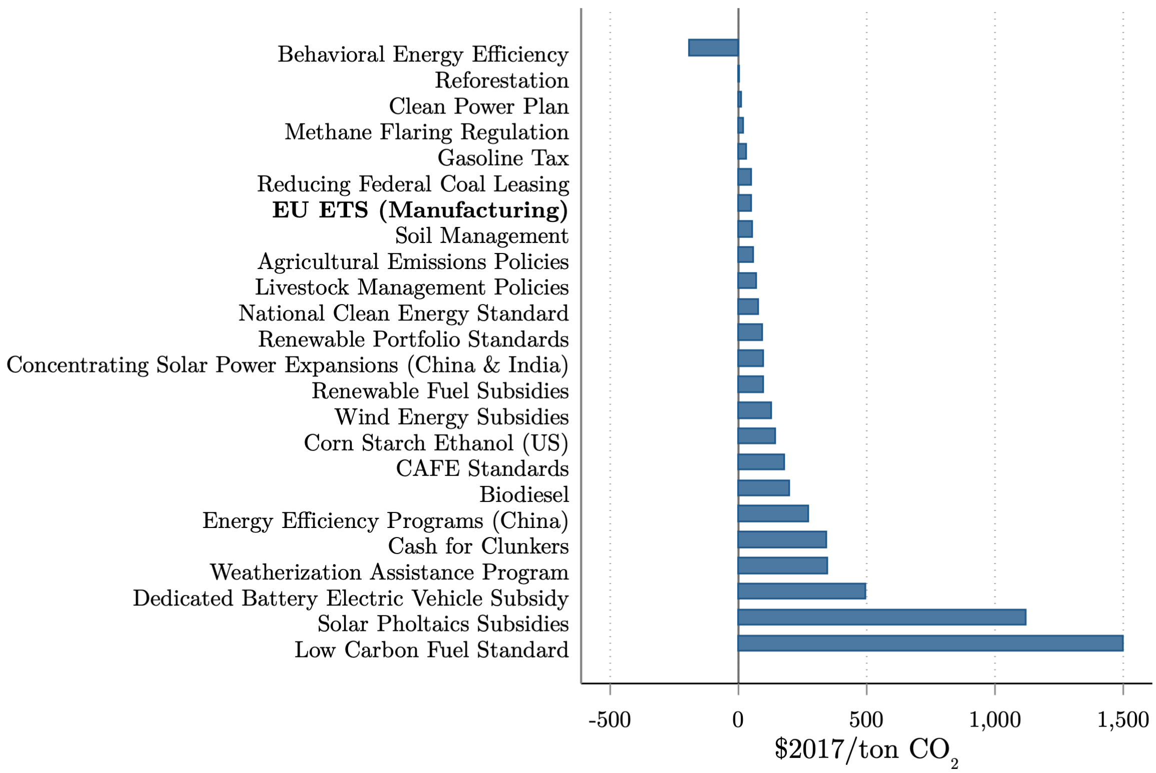
We calculate that between 2005 and 2012 aggregate emissions would on average have been 5.4 million tonnes higher each year if there was no EU ETS. Compared to 2004 emissions, this accounts for 28% of the aggregate emissions reduction during this period. Using the linear trend in emissions prior to 2005 as a benchmark instead of emissions in 2004 would lead us to attribute 47% of the aggregate emissions reduction during this period to the EU ETS. These calculations highlight the importance of causal research designs for evaluating the efficacy of climate policy. 53-72% of the aggregate emissions reductions in our data are driven by other factors, e.g., structural economic change, energy efficiency improvements, and the Great Recession to name three. Drawing inferences about the effectiveness of the ETS based on aggregate patterns and trend-breaks would lead us to vastly overestimate the efficacy of the EU ETS.

These emissions reductions occurred in spite of carbon prices averaging at a rather low \$21.35 per tonne (\$2017) during Phase II. Arguably, the average abatement costs per tonne of CO_2 must have been lower, for otherwise it would have been more profitable for firms to purchase permits instead of reducing emissions. Does that make the EU ETS an expensive policy? Previous research on air pollution regulation has established that the overall cost of market-based instruments compares favorably with that of non-market based approaches (Carlson et al., 2000; Fowlie et al., 2012; Gillingham & Stock, 2018). In Figure 5 we compare the estimated cost per tonne of CO_2 (\$2017) for 25 climate change mitigation policies. The estimate for the EU ETS is based on the maximum price during Phase II – \$52.68. This is a conservative cost estimate as above this cost it would have been cheaper for firms to buy emission permits instead. Estimates for other climate change mitigation policies come from Gillingham & Stock (2018). Even when we use the maximum cost per tonne of CO_2, the EU ETS is ranked 7th. If we use the average Phase II price instead (\$21.35), which is still likely to be very conservative, the EU ETS is ranked 5th. We caveat that this exercise assumes that the EUA price is unaffected by the other energy and climate policies discussed in Appendix B.5. While we do not think that these policies differentially affected ETS firms, their existence may have had an aggregate effect, resulting in a lower equilibrium permit price. This would have the effect of making the ETS as a whole, i.e., including the electricity sector, appear cheaper than it would have been if these policies did not exist.

7 Conclusion

In the context of the world's largest carbon market, we have presented evidence that market-based regulatory instruments have the potential to reduce carbon emissions without imposing significant economic losses on regulated firms. Firms invested in new technology, lowered the carbon intensity of production. For a subset of firms, these investments appear to have delivered cost savings or efficiency increases offsetting the direct increase in input costs associated with the regulation. We

Figure 5: Comparing the EU ETS to other Climate Change Mitigation Policies



Notes: This figure ranks different climate change policies by the estimated cost of reducing a tonne of CO_2 in $2017. The value chosen for the EU ETS is the maximum permit price that was observed during phase II – €29.33 on 1st July 2008. We then convert this to U.S. dollars using the exchange rate on that day and then account for inflation between 2008 and 2017. The maximum cost of reducing a tonne of CO_2 was $52.68. The actual cost was likely far lower, as this is the maximum price at which firms would have been indifferent between reducing emissions and buying permits. Despite this conservative choice, the EU ETS is ranked 7th out of 25. The cost of other policies are taken from Gillingham & Stock (2018). Where multiple estimates exist for the same policy we take the average across all estimates.

find little evidence that carbon leakage played a meaningful role in contributing to these emissions reductions, indicating that, at least in this context, the EU ETS helped to mitigate global climate change.

Our results contrast with the impacts of command-and-control regulations that impose one-size-fits-all regulatory standards for industrial air pollution emissions. While also delivering improvements in environmental quality, such non-market-based policies have been shown to have negative effects on firm performance (Becker & Henderson, 2000; Greenstone, 2002; Greenstone et al., 2012; Walker, 2013; He et al., 2020).

We note caveats. Despite the significant effect that the EU ETS has had on emissions, these results should not be taken as a blank endorsement of market-based regulatory instruments. Our findings have focused on the response of manufacturing firms in one market, and on one market-based regulatory instrument – emission trading schemes. Our context is one in which compliance is high and corruption low.

Furthermore, while we present evidence that for a subset of firms the ETS regulation may have increased awareness of cost-saving or efficiency increasing opportunities, our results do not imply that the emission reductions have been without cost. Finally, our results do not guarantee that the ETS operates efficiently. Credit constraints, other information asymmetries, market power in product markets, transaction costs, and other sources of market failure could all affect the efficiency of the scheme. Understanding how other market failures interact with environmental regulations remains an interesting and important direction for future research.

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Online Appendix

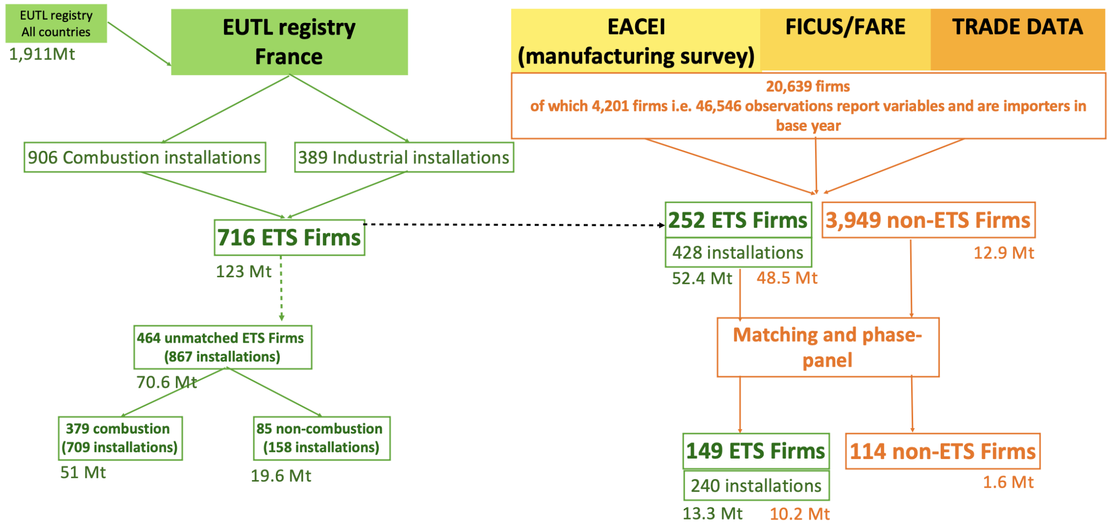
Contents

A Data Appendix

A.1 Sample Construction

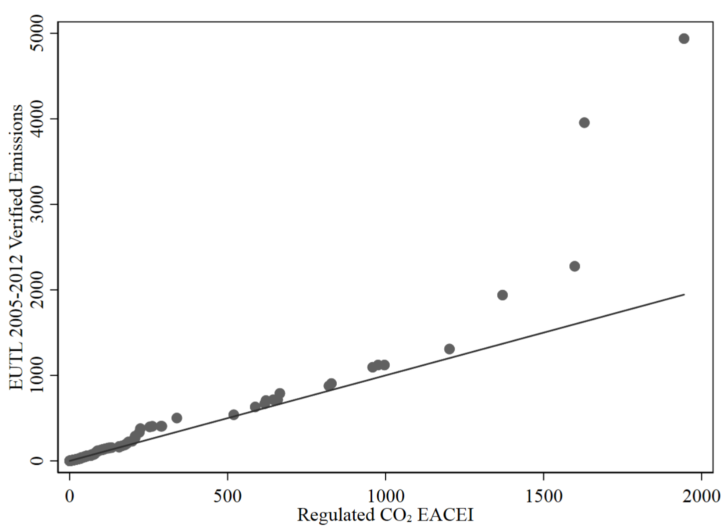
Figure A.1 presents a visualization of our sample construction process, whereby we combine data publicly available from the European Union Transaction Log (EUTL) registry (on the left) with statistical firm-level data made available to researchers through the CASD (on the right). Regarding the EUTL, data on participation in the ETS for France includes 1,295 installations that are reported to have participated (at least for one year) in Phase I and/or Phase II of the EU ETS. 906 of these installations are combustion installations. These combustion installations are largely in the electricity sector, although manufacturing installations are also engaged in combustion, e.g. steel. All installations were matched to a SIREN number, a firm level identifier. The match was conducted using a look-up table provided by the French authorities, or through a manual name and address-based matching process. In some cases, the manual process identified changes in SIREN or identifiers, or acquisitions, in which cases we aim to aggregate at the most appropriate firm-level. Some firms have more than one installation regulated under the EU ETS. The 1,295 installations in the EUTL are identified to be part of 716 firms. Their average annual emissions reported to the EU ETS (verified emissions) total to 123 million tonnes of CO_2. Note that we exclude from this firms that are only included in the EU ETS through aviation, which was initiated in 2012. Through the CASD, we link energy-use (EACEI) survey data available for manufacturing installations to trade and balance-sheet (FICUS/FARE) data available for manufacturing firms. Firms are included in our sample if they report at least in 2000 and one other year positive employment, CO_2 emissions, energy use, value added and capital. We also impose that they report positive imports in 2000 given all ETS firms were importers in that year. This corresponds to 4,201 firms. We match these firms on the basis of their SIREN identifier to those from the EUTL registry and identify 252 EU ETS firms in our dataset, corresponding to a total of 52.4 million tonnes of CO_2 average annual verified emissions. 81% of the 464 ETS firms that are not matched to our administrative data are combustion installations, and most likely power plants. The non-combustion unmatched firms are either non-manufacturing or not observed in our data. When comparing the verified emissions reported in the market's EUTL (in green on the left of each corresponding box) to the emissions resulting from fuels usage reported in the EACEI (in orange on the right of each corresponding box), they are on aggregate at a similar level. However, if comparing these for each firm, one must keep in mind that it is unlikely for these to be perfectly equal. Apart from statistical or reporting discrepancies, the main reason for this is that in some industrial sectors, such as cement, chemicals or fertilisers, carbon emissions do not only arise from the combustion of fossil fuels, but also from the industrial processes themselves. In France, it is estimated that a quarter of GHG emissions from manufacturing are process emissions, and half of these from the decarbonation process (for example when limestone is heated). The EACEI only reports the usage of fuels, from which we impute CO_2 emissions, and their correlation is represented in the quantile-quantile plot against verified emissions, in Figure A.2. We see that for the vast majority of the distribution measured and reported emissions map closely to each other. The gap is very close to the 45-degree line except for a few firms at higher levels of emissions where verified emissions, that include combustion and process emissions, are larger than EACEI emissions that only include combustion of fossil fuels. Given the small number of firms with such a gap, the correlation is 0.96 and significant at the 1%.

Figure A.1: Sample Construction



Notes: This figure presents the different steps involved in constructing our sample of analysis. The EUTL is the EU ETS registry publicly available. The EACEI, FICUS/FARE and Trade data are made available by the CASD. All datasets are described in Section 3. The figures in green on the left below each text boxes report the total of average annual emissions reported in the EUTL between 2005 and 2012 for that group of firms in million tonnes of CO_2. The figures in orange below the text boxes on right report the total average emissions from combustion computed from the EACEI in million tonnes of CO_2 between 2005 and 2012. The 252 ETS and 3.949 non-ETS firms represent the full sample pre-matched. The 149 ETS and 114 non-ETS firms represent the matched sample.

Figure A.2: Quantile-Quantile Plot



Notes: This figure presents a quantile-quantile plot of the quantiles of CO_2 verified emissions reported in the EUTL against the quantiles of CO_2 emissions computed from the EACEI for each firm in our full sample. The emissions for both variables are the average of these annual measures between 2005 and 2012. The line represents a 45 degrees along which both variables are equal. The plot is truncated to include only firms whose average verified emissions in the EUTL are below 10 milliontonnes.

Table A.1: Descriptive Statistics – Matched Sample

	(1) Observations	(2) Mean	(3) St. Dev.	(4) 10th perc.	(5) Median	(6) 90th perc.
CO_2	4,156	49.224	136.605	2.090	13.3621	90.523
Employment	4,156	601.866	1,111.713	87	319	1,200
Value Added	4,156	46.753	105.508	4.956	20.478	97.012
Capital Stock	4,156	119.211	233.178	12.069	59.629	250.341
CO_2/VA	4,156	2.483	10.740	0.0568	0.890	4.640
Total Imports	4,156	113.707	632.207	2.3	24.568	199.736
Carbon Intensive Imports	4,156	1.231	6.251	0.012	0.191	1.632
Gas Share	4,156	0.760	0.362	0	0.977	1
Electricity Share	4,156	0.321	0.217	0.101	0.257	0.658
Pollution Control Investment:						
Measurement	3,800	8.107	45.485	0	0	10
Integrated	2,760	42.637	248.454	0	0	50.275
Specific	2,760	51.808	562.109	0	0	43.5

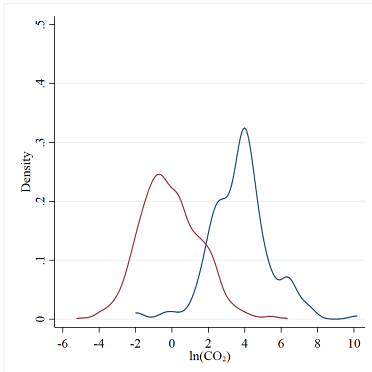
Notes: Column 1 reports the number of observations (firms $\times$ years), Columns 2 and 3 report the mean and standard deviation of each variable measured across all years of data. Columns 4 to 6 present the median, 10th percentile and 90th percentile. Units CO_2 – thousands of tonnes of CO_2; Value Added – millions of Euros; Employment – full-time equivalent employees; Capital – millions of Euros; CO_2/VA – tonnes of CO_2 per thousand Euros of value added; Imports – millions of Euros; Gas Share – Gas CO_2/CO_2; Purchased Electricity/Total Energy Consumed in tonnes of oil equivalent. Electricity bought is converted to tonnes of oil equivalent using the conversion factor toe = MWh$\times$0.086; Pollution control investment – Thousands of Euros.

Table A.2: Share of Regulated Emissions and Group Size – Matched Sample

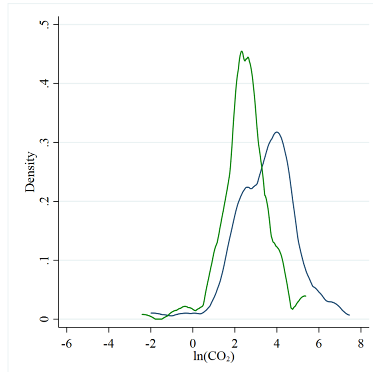
Sample	Regulated CO_2/CO_2		Number of Firms	
	ETS	Non-ETS	ETS	Non-ETS
Steel (16)	93.94%	0%	9	5
Ceramics (21)	96.15%	0%	8	11
Glass (22)	93.21%	0%	15	10
Plastics and Rubber (25)	85.74%	0%	4	6
Organic Chemicals (26)	86.20%	0%	12	11
Pharmaceuticals (28)	68.22%	0%	7	9
Textiles and Leather (34)	69.76%	0%	6	9
Paper and Pulp (35)	90.49%	0%	48	17
Various industries (38)	100%	0%	9	6
Other (0)	80.34%	0%	31	30

Notes: Sector classifications are defined using the NCE nomenclature. Statistics are calculated using observations in the year 2000. We construct the sector ”Other” to satisfy statistical disclosure constraints. This sector includes all firms that are not in the listed NCE sectors.

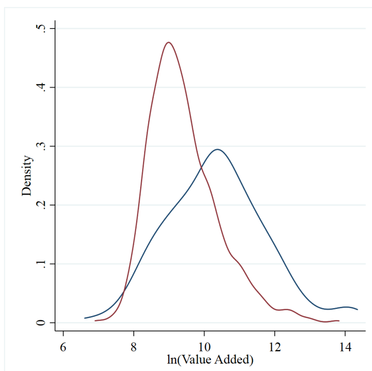
Figure A.3: Density plots showing differences between regulated and unregulated firms in the pre- and post-match samples (CO_2 Emissions, Value Added, and Employment)



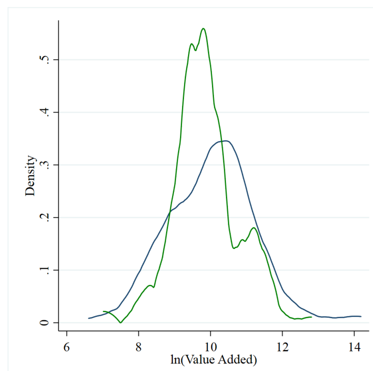
(a) CO_2 (Unmatched)



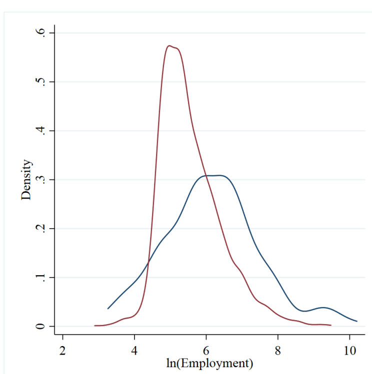
(b) CO_2 (Matched)



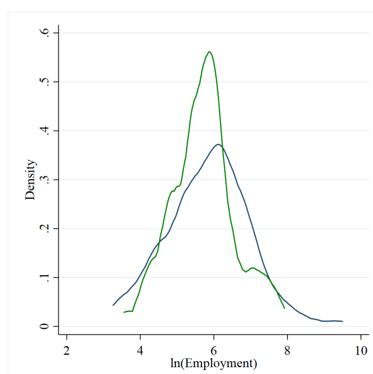
(c) Value Added (Unmatched)



(d) Value Added (Matched)



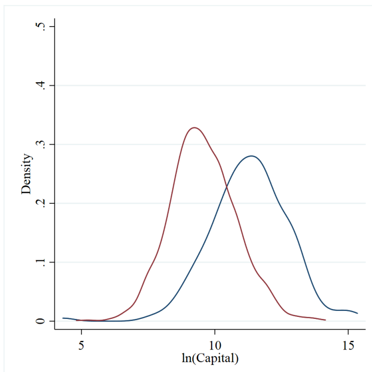
(a) Employment (Unmatched)



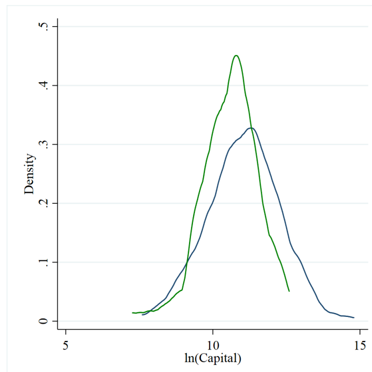
(b) Employment(Matched)

Notes: The figures report the density plots of log CO_2 emissions, log value added, and log employment in the year 2000, our base year. In all figures the blue lines represent regulated firms. In the unmatched sample the distribution of each variable for unregulated firms is represented in red. For the matched sample the distribution of each variable for unregulated firms in represented in green.

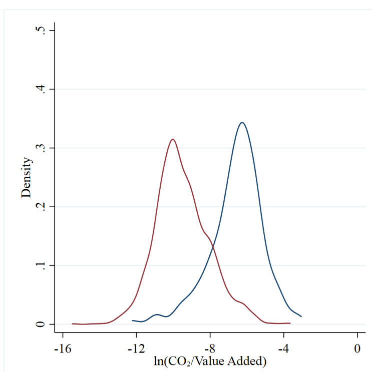
Figure A.4: Density plots showing differences between regulated and unregulated firms in the pre- and post-match samples (Capital and CO_2/Value Added)



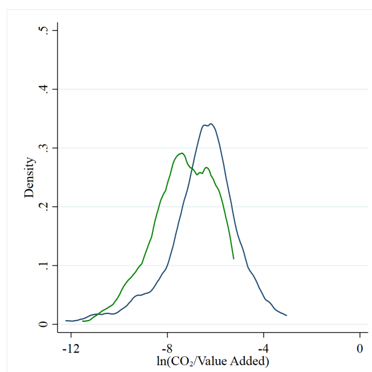
(a) Capital (Unmatched)



(b) Capital (Matched)



(c) CO_2/VA (Unmatched)



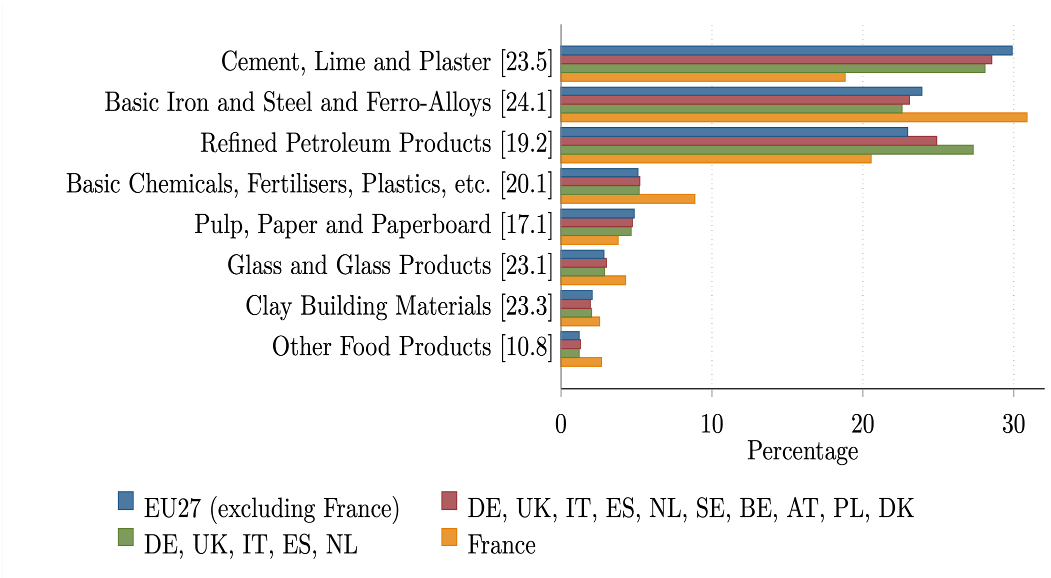
(d) CO_2/VA (Matched)

Notes: The figures report the density plots of log capital and log emissions intensity defined as CO_2 emissions/value added in the year 2000, our base year. In all figures the blue lines represent regulated firms. In the unmatched sample the distribution of each variable for unregulated firms is represented in red. For the matched sample the distribution of each variable for unregulated firms in represented in green.

A.2 Representativeness

To assess how representative our sample of French manufacturing firms is compared to the broader set of EU manufacturing firms regulated by the EU ETS, we downloaded emissions data from http://www.euets.info/ which augments data on verified CO_2 emissions from the European Union Transaction Log (EUTL) with NACE industry classifications from EU sources. We compute the share of CO_2 emissions by industry in total manufacturing emissions at the 3-digit NACE code level. Figure A.5 compares this statistic between ETS firms in France (orange) and the remaining EU countries (EU27 excluding France, in blue) for the most emissions intensive sectors, based on average verified emissions at the beginning of the ETS (2005 and 2006).

Figure A.5: CO_2 emissions intensity across 3-digit manufacturing industies

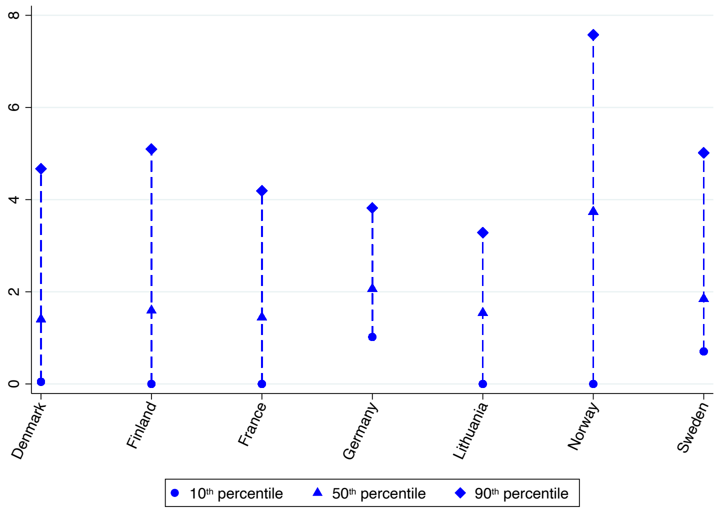


Source: Own calculations based on www.euets.info.

The four most emissions-intensive industries in France also constitute the top four in the rest of Europe, although the ranking among the top three is not the same. While the larger role of the chemical industry is confirmed, it seems that cement plays a smaller and iron & steel a larger role in France than in the rest of the EU. In sum, regulated emissions in France do not exactly correspond to the EU27-average, but can be considered representative at a broader level. This conclusion holds true also when we compare France to groups of countries that can be considered closer competitors, such as the EU top five economies excluding France (Germany, UK, Italy, Spain, and the Netherlands) or the top ten (top five plus Poland, Belgium, Sweden, Austria and Ireland).

Aside from the emissions share of certain industries, we compare the distribution of carbon intensity across firms in different countries to assess representativeness. This necessitates a measure that relates CO_2 emissions to output or other inputs. Obtaining comparable microdata at the firm level is not trivial and is the subject of ongoing research. Wagner et al. (2020) compiled and

Figure A.6: CO_2 emissions per worker in the ETS sector



Notes: Figure shows the natural log of direct CO_2 emissions per full-time employee in ETS firms regulated. Emissions are averaged over the years 2004,2007 and 2012. Own calculations based on Figure 7 in Wagner et al. (2020)

analyzed administrative microdata on energy use and resulting CO_2 emissions from seven European countries, including France. This allows us to construct CO_2 intensity measures in a way that is consistent across countries and allows us to compare our French manufacturing sample to its equivalent in other countries. Figure A.6 shows selected deciles of the natural log of direct CO_2 emissions per full-time employee in ETS firms (emissions are averaged over the years 2004, 2007 and 2012). In terms of median emissions, French manufacturing is less CO_2 intensive than Norwegian manufacturing, but very similar to those of Denmark, Finland, Lithuania. The median German and Swedish ETS firm is more emissions intensive than its French counterpart, but not to a large degree, and the distributions largely overlap.

B Additional Results and Robustness

B.1 Full-Sample Difference-in-Differences Results

Here we present our main results using the full sample of firms. As documented in Table 1 there are very large baseline differences between ETS and unmatched non-ETS firms, raising concerns about the potential validity of parallel trends for the full sample. Figure 1 suggests that there are not meaningful differences in the trajectories of unmatched non-ETS and ETS firms in the raw data prior to the announcement of the ETS, but that ETS and unmatched non-ETS firms start to diverge during the announcement phase. In contrast, matched non-ETS firms, follow a similar trajectory to ETS firms until the policy comes into effect, which alongside smaller baseline differences (Table 1) motivates our choice to use the matched sample in our main analysis.

Table B.1 and B.2 present descriptive statistics for the full sample. Table B.3 presents difference-in-differences results using our full sample. Figure B.1 event study estimates of the results in Table B.3. In the full sample, we estimate similar results to the matched sample, however, the

Table B.1: Descriptive Statistics – Full Sample

	(1) Observations	(2) Mean	(3) St. Dev.	(4) 10th perc.	(5) Median	(6) 90th perc.
CO_2	46,546	23.007	439.906	.139	1.105	15.814
Employment	46,546	456.125	994.231	93	213	889
Value Added	46,546	29.341	82.108	3.522	10.478	58.189
Capital Stock	46,546	53.228	175.094	3.372	16.509	107.360
CO_2/VA	46,546	0.756	10.676	0.0146	0.090	1.237
Total Imports	46,546	48.859	241.562	2.300	9.194	89.908
Carbon Intensive Imports	46,546	0.326	2.276	0.002	0.049	0.516
Gas Share	46,546	0.672	0.422	0	0.958	1
Electricity Share	46,546	0.498	0.245	0.187	0.474	0.856
Pollution Control Investments:						
Measurement	36,567	2.877	27.839	0	0	0.376
Integrated	23,998	20.011	151.794	0	0	13.704
Specific	23,998	18.929	228.147	0	0	6.812

Notes: Column 1 reports the number of observations (firms $\times$ years), Columns 2 and 3 report the mean and standard deviation of each variable measured across all years of data. Columns 4 to 6 present the median, 10th percentile and 90th percentile. Units CO_2 – thousands of tonnes of CO_2; Value Added – millions of Euros; Employment – full-time equivalent employees; Capital – millions of Euros; CO_2/VA – tonnes of CO_2 per thousand Euros of value added; Imports – millions of Euros; Gas Share – Gas CO_2/CO_2; Electricity Share – Purchased Electricity/Total Energy Consumed in tonnes of oil equivalent. Electricity bought is converted to tonnes of oil equivalent using the conversion factor toe = MWh$\times$0.086; Pollution control investment – Thousands of Euros.

magnitudes of the emissions reductions in Phase I and Phase II are much larger (-22% and -33% respectively). Unlike the matched sample we also estimate small but statistically significant differential reductions in emissions for regulated firms during the announcement period and prior to the announcement of the EU ETS. While this is a violation of the parallel trends assumption, the estimate results do not reflect a common declining trend over time, this would be the case if emissions were differentially higher for regulated firms prior to the announcement of the EU ETS. We also do not see any differential pre-trends for the other outcome variables, all of which reflect small and precise null effects. While there does not appear to be any systematic violation of the parallel trends, the small violation for emissions, the large baseline differences between treatment and control firms, and much larger treatment effects, including announcement period declines provide less confidence than the matched sample, which does not face these issues. Nevertheless, it is encouraging to see qualitatively similar patterns in the full sample, suggesting that the insights from our matched sample may have some external validity and be broadly representative of the effect of the ETS on regulated firms.

Table B.2: Descriptive Statistics by Treatment Status and Sector – Full Sample

Sample	Mean CO_2		Regulated CO_2/CO_2		Mean Employment		Number of Firms	
	ETS	Non-ETS	ETS	Non-ETS	ETS	Non-ETS	ETS	Non-ETS
Steel (16)	2083.768	121.114	92.29%	0%	2140.385	405.294	13	17
Cement and Lime (20)	346.486	145.658	86.20%	0%	379.600	734.200	15	5
Ceramics (21)	38.844	15.850	96.92%	0%	266.700	289.168	10	101
Glass (22)	148.590	7.314	91.53%	0%	1,274.348	263.158	23	38
Inorganic Chemicals (24)	341.539	55.597	100%	0%	238.400	327.769	5	26
Plastics and Rubber (25)	76.406	64.640	88.60%	0%	414.000	237.370	5	27
Organic Chemicals (26)	321.652	36.432	81.17%	0%	1,366.350	376.326	20	92
Pharmaceuticals (28)	14.747	3.990	67.55%	0%	1,221.125	542.069	8	175
Electronic and Electrical Engineering (31)	21.905	2.426	78.41%	0%	5,681.250	692.679	4	371
Textiles and Leather (34)	19.434	2.258	77.32%	0%	583.375	237.608	8	360
Pulp and Paper (35)	59.681	9.116	86.28%	0%	426.422	232.473	64	131
Rubber Products (36)	124.897	4.954	69.17%	0%	7,221.800	488.824	5	51
Plastic Material Transformation(37)	34.334	1.318	100%	0%	590.250	296.796	4	269
Various (38)	25.396	1.711	100%	0%	444.778	293.435	9	382
Other (0)	135.771	5.745	76.75%	0%	1,429.254	388.691	59	1,904

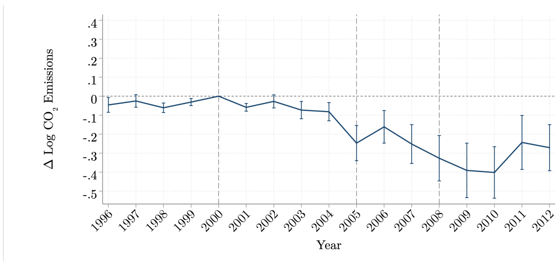
Notes: Sector classifications are defined using the NCE nomenclature. Means are calculated using observations in the year 2000. We construct the sector ”Other” to satisfy statistical disclosure constraints. This sector includes all firms that are not in the listed NCE sectors. Units: CO_2 – thousands of tonnes of CO_2; Employment – full-time equivalent employees

Table B.3: The Effect of the EU ETS on the Environmental and Economic Performance of Firms – Full Sample

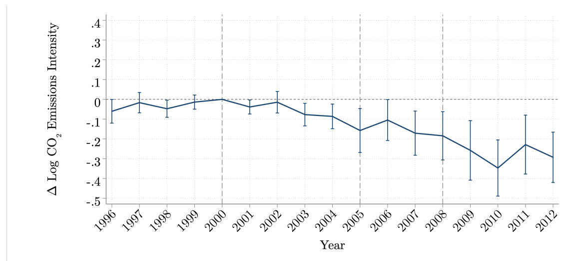
	(1)	(2)	(3)	(4)	(5)
	Δ log(CO_2)	Δ log(Value Added)	Δ log(Emp.)	Δ log(Capital)	Δ log(CO_2/VA)
Pre-Announcement	-0.0408***	-0.0334	-0.00956	-0.0243	-0.0353*
	(0.0124)	(0.0281)	(0.0184)	(0.0215)	(0.0203)
Announcement Period	-0.0627***	0.0150	0.000548	0.00423	-0.0595***
	(0.0149)	(0.0279)	(0.0129)	(0.0140)	(0.0205)
Trading Phase I	-0.220***	-0.0631	-0.0149	0.0214	-0.144***
	(0.0432)	(0.0509)	(0.0323)	(0.0385)	(0.0493)
Trading Phase II	-0.333***	-0.0468	-0.0253	0.00523	-0.264***
	(0.0600)	(0.0650)	(0.0466)	(0.0603)	(0.0604)
Mean in 2000	229.351	84.655	1,140.222	204.422	3.058
Observations	46,546	46,546	46,546	46,546	46,546

Notes: This table presents estimates from OLS regressions estimated on the full sample. Standard errors are clustered at the firm-level. Each estimate reflects the difference between regulated firm and unregulated firm outcomes relative to the year 2000. We present estimates for four time periods: prior to the announcement of the EU ETS, during the announcement period and during Phase I and Phase II of the EU ETS. Means are reported for ETS firms in 2000. Units: CO_2 – thousands of tonnes of CO_2; Value Added – millions of Euros; Employment – full-time equivalent employees; Capital – millions of Euros; CO_2/VA units – thousands of tonnes of CO_2 per thousand Euros of value added. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

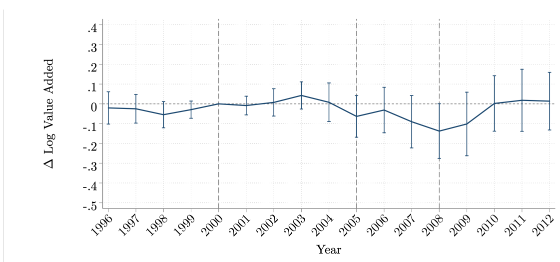
Figure B.1: The Effect of the EU Emissions Trading Scheme on the Environmental and Economic Performance of Firms – Full Sample



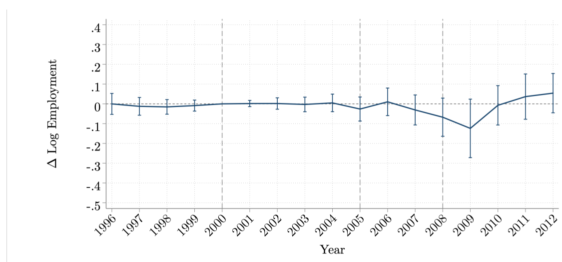
(a) CO_2 Emissions



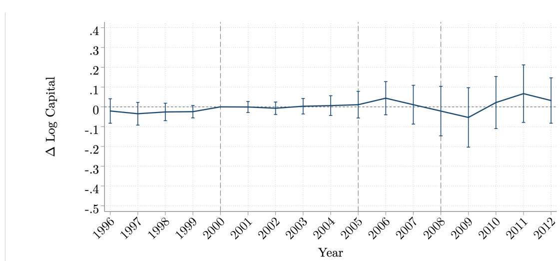
(b) Carbon Intensity



(c) Value Added



(d) Employment



(e) Capital Stock

Notes: This figures presents estimates from OLS regressions, estimated on the full sample. Standard errors are clustered at the firm-level. All variables are in logs and normalized at the year 2000. Vertical red lines relate to the different phases of the EU ETS. The EU ETS was announced in 2000 and the first phase began in 2005. Phase II of the EU ETS began in 2008. Standard errors are clustered at the firm-level.

B.2 Alternative Matching Specifications

In the baseline specification we match 149 treated firms with replacement using 114 untreated firms as controls. Table B.4 presents results for log emissions when using a range of alternative matching specifications. The estimated reduction in emissions in Phase I and Phase II is robust to those alternative matching specifications. Our other outcome variables are also robust to different matching specifications.

Table B.4: Alternative Matching specifications

	Δ log(CO_2 Emissions)							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-Announcement	0.028	0.024	-0.027	0.013	-0.003	-0.001	-0.012	0.028
	(0.021)	(0.020)	(0.020)	(0.019)	(0.019)	(0.018)	(0.017)	(0.021)
Announcement Period	0.014	0.014	-0.009	0.012	0.007	0.009	-0.002	0.007
	(0.025)	(0.025)	(0.057)	(0.026)	(0.024)	(0.024)	(0.023)	(0.025)
Trading Phase I	-0.140**	-0.139**	-0.116**	-0.112**	-0.113**	-0.104*	-0.118**	-0.146***
	(0.057)	(0.058)	(0.054)	(0.057)	(0.056)	(0.054)	(0.052)	(0.056)
Trading Phase II	-0.163**	-0.156**	-0.126*	-0.135*	-0.129*	-0.119*	-0.137**	-0.168**
	(0.075)	(0.074)	(0.074)	(0.073)	(0.072)	(0.069)	(0.068)	(0.072)
Observations	2,348	2,348	1,910	4,338	6,280	8,168	9,994	2,284
# Regulated Firms	149	149	124	149	149	149	149	145
Alternative Specification	Baseline	Fewer Matching Variables	Without Replacement	2 NN	3 NN	4 NN	5NN	Common Support

Notes: These estimates are the result of OLS regressions, estimated on a matched sample. They provide the difference between regulated firm and unregulated firm outcomes prior to the announcement of the EU ETS, during the announcement period and during Phase I and Phase II of the EU ETS. Each coefficient represents the difference relative to the year 2000. Standard errors are two-way clustered by firm and matching group. Different matching specifications are presented in each column as specified by the line "Alternative Specification". Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

B.3 Alternative Distance Restrictions

Table B.5 presents an evaluation of how sensitive the baseline matched sample results are to the choice of distance restriction that are imposed when matching treated to control firms. Our main specification from Table 2 is reproduced in column 1. We find that when imposing greater restrictions on the difference between treatment and control firms the significance and magnitude of the reduction in CO_2 emissions in both phases is reduced. Dropping 25% of the sample results in the Phase I and Phase II reductions in emissions losing statistical significance. The magnitude of the coefficient estimates in Phase I and Phase II, however, remain non-trivial at around -10%.

Table B.5: Distance restrictions

	Δ log(CO_2 emissions)				
	(1)	(2)	(3)	(4)	(5)
Pre-Announcement	0.028	0.030	0.033	0.039*	0.039*
	(0.021)	(0.021)	(0.021)	(0.021)	(0.023)
Announcement Period	0.014	0.014	0.016	0.024	0.036
	(0.025)	(0.026)	(0.026)	(0.027)	(0.028)
Trading Phase I	-0.140**	-0.144**	-0.124**	-0.105*	-0.095
	(0.057)	(0.058)	(0.056)	(0.055)	(0.061)
Trading Phase II	-0.163**	-0.166**	-0.129*	-0.097	-0.107
	(0.075)	(0.075)	(0.072)	(0.073)	(0.083)
Distance Cutoff	No Restrictions	99th Percentile	95th percentile	90th Percentile	75th Percentile
Observations	2,348	2,318	2,237	2,109	1,767
# of Regulated Firms	149	147	142	135	115

Notes: These estimates are the result of OLS regressions, estimated on a matched sample. They provide the difference between regulated firm and unregulated firm outcomes prior to the announcement of the EU ETS, during the announcement period and during Phase I and Phase II of the EU ETS. Each coefficient represents the difference relative to the year 2000. Distance restrictions between treatment and control firms are imposed at different percentiles. Standard errors are two-way clustered by firm and matching group. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

B.4 The Great Recession

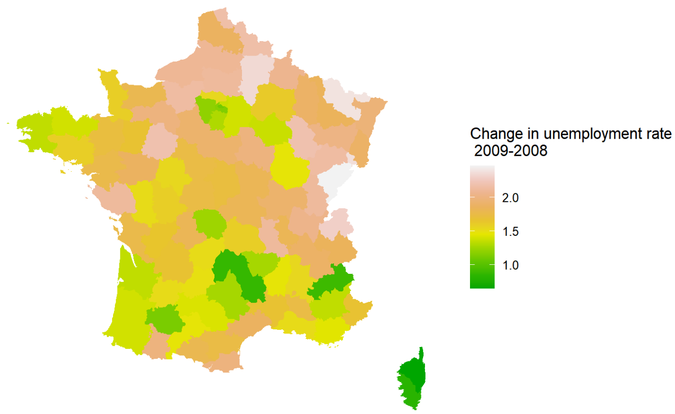
As discussed in Section 4.2, part of our treatment period overlaps with the Great Recession of 2008. Whilst the US saw its GDP beginning to decline in 2008, the French economy stagnated in that year with a 0.25% increase in GDP, and entered the recession only in 2009. This Appendix seeks to test whether our estimates of the impact of the EU ETS on emissions and other economic outcomes are driven by the Great Recession rather than the policy.

Idiosyncratic shocks over time, such as a recession, underline the need to conduct evaluations with firm level data comparing treated and non-treated firms. However, there remains a concern that such a dramatic shock interacts differentially with the somewhat larger ETS firms compared to the untreated control firms. The issue can be addressed by identifying meaningful variation in the severity of the Great Recession shock across firms in our sample. To this end, consider the following regression model:

$$Y_{it} = \alpha ETS_i \times D_t + \theta D_t + \beta_E ETS_i + \beta_R REC_{k(i)t} + \gamma REC_{k(i)t} \times ETS_i + \epsilon_{it}$$

where firms i differ in treatment status (ETS) and in terms of a recession shock $REC_{k(i)t}$. The indicator variable D_t is one in all periods when the ETS is active. The shock is assumed to be common for firms in the same cluster $k(\cdot)$, e.g. the same geographic area or sector. Moreover, even if faced with the same recession shock, the effect will be different for the type of firms that are part of the ETS where $ETS_i = 1$. For ease of notation, we assume that the recession shock is zero in $t = 0$, the base year. Taking within-firm differences between year t and the base year, we

Figure B.2: Spatial Variability in Depth of Great Recession



Notes: Change in unemployment level for each of the 96 French departments between 2008 and 2009 measured in percentage. Each year's unemployment is calculated as the mean of the year's quarterly figures. *Source:* INSEE, https://www.insee.fr/fr/statistiques/series/102760732

compute differences-in-differences between and ETS firm i and a non-ETS control firms l as

$$\begin{aligned}\Delta^2 Y_{il,t} &= Y_{it} - Y_{it} - (Y_{l0} - Y_{l0}) \\ &= \alpha + (\beta_R + \gamma) \times REC_{k(i)t} - \beta_R REC_{k(l)t} + \Delta^2 \nu_{il,t} \qquad (22)\end{aligned}$$

where $\Delta^2 \nu_{il,t} = \epsilon_{it} - \epsilon_{io} - (\epsilon_{lt} - \epsilon_{lo})$. This equation suggests that we can recover an unbiased ETS estimate of the policy effect α by regressing $\Delta^2 Y_{il,t}$ on the treatment dummy while also controlling for both regression shocks, the one the treated firm, $REC_{k(i)t}$, and of its matched control firm and $REC_{k(l)t}$.

To implement this empirically, we construct two different ks; one spatial and one sectoral measure of recession exposure that proxies for the recession shock REC_k. At the geographic level, we compute for each department (*département*) d the change in unemployment levels U between 2008 and 2009, ΔU_d. As shown in Figure B.2, some departments (in green) saw very minor increases in unemployment rates whilst others, such as the Doubs, suffered a deeper recession with increases of up to 2.5%. At the sector level, we measure the change in employment levels E between 2008 and 2009 by 4-digit NAF s, ΔE_s, aggregating firm-level employment from FICUS/FARE by year and s. The higher the decrease in employment, the harder the hit of the recession: employment decreased strongly in some sectors (such as the *Manufacture of optical instruments and photographic equipment*, where it fell by 50%) but increased in others. Exposure to the Great Recession $REC_{k(i)t}$ is thus defined as ΔU_d (for the department level) or ΔE_s (for the sector level) if $t = 2008$ or $t = 2009$ and zero otherwise. Table B.6 shows the results of estimating equation (22) where we control for the two $REC_{k(j)t}$'s, of both the treated and matched untreated firms. The inclusion of these variables has no effect on our Phase I treatment effect as should be expected. In Phase II the coefficient is slightly attenuated from -16.3% in our main results to -14.5%.

Table B.6: Controlling for the Great Recession

	(1)	(2)	(3)	(4)	(5)
	Δ log(CO_2)	Δ log(Value Added)	Δ log(Emp.)	Δ log(Capital)	Δ log(CO_2/VA)
Pre-Announcement	0.028	0.009	0.002	-0.012	0.022
	(0.021)	(0.039)	(0.025)	(0.025)	(0.037)
Announcement Period	0.014	0.014	-0.002	0.014	0.013
	(0.025)	(0.040)	(0.019)	(0.021)	(0.034)
Trading Phase I	-0.140**	-0.050	0.005	0.083*	-0.099
	(0.057)	(0.085)	(0.036)	(0.046)	(0.068)
Trading Phase II	-0.145*	0.120	0.084	0.112*	-0.171**
	(0.081)	(0.087)	(0.055)	(0.065)	(0.085)
Great Recession	-0.060	-0.033	-0.032	0.101	0.020
(Departement) Treated	(0.126)	(0.145)	(0.107)	(0.112)	(0.140)
Great Recession	-0.836	-3.547**	-2.275***	-2.105**	2.625***
(Sector) Treated	(0.125)	(0.136)	(0.100)	(0.101)	(0.136)
Great Recession	0.033	0.019	-0.012	-0.091	-0.035
(Departement) Control	(0.125)	(0.136)	(0.100)	(0.101)	(0.136)
Great Recession	0.444	0.209	0.473	0.077	-0.231
(Sector) Control	(1.230)	(1.670)	(1.001)	(0.856)	(0.679)
Mean in 2000	82.107	55.600	684.215	132.919	3.398
Observations	2,348	2,348	2,348	2,348	2,348

Notes: This table presents estimates from OLS regressions, estimated on a matched sample. Standard errors are clustered in two ways, at the firm-level and at the matching group level. Each estimate reflects the difference between regulated firm and unregulated firm outcomes relative to the year 2000. We present estimates for four time periods: prior to the announcement of the EU ETS, during the announcement period and during Phase I and Phase II of the EU ETS. We control for measures of the Great Recession severity in the Departement region and NAF sectors of the treated and matched control firms. Means are reported for ETS firms in 2000. Units: CO_2 – thousands of tonnes of CO_2; Value Added – millions of Euros; Employment – full-time equivalent employees; Capital – millions of Euros; CO_2/VA units – thousands of tonnes of CO_2 per thousand Euros of value added. Great Recession variables are in percentage. Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

B.5 Overlapping policies

Here we discuss the potential for other energy and climate policy interventions to interact with EU ETS incentives during our study period. If interactions with the EU ETS regulations induced systematic differences in firm behavior across treated and control firms we would be unable to separately identify the effects of the EU ETS from other policies. In what follows, we list and review overlapping policies and discuss their potential to confound our results.

Power purchase obligation and guaranteed feed-in tariffs Since 2003, the French electricity company EDF has been obliged to purchase power generated from certain sources at a guaranteed rate.

This policy overlaps with our sample period and might have provided incentives for firms to generate electricity. A threat to identification would arise from this policy if treated and control firms perceived such incentives differently. Since the policy was introduced prior to the implementation of the ETS, we can test for this directly by looking at pre-trends in outcome variables that speak directly to those incentives. In Figures 1 and 2a we do not see a drop in emissions until 2005, indicating that the 2003 purchase power agreements did not have an immediate effect on emissions. In Table B.7 we see that in 2000 35% of firms generated electricity from thermal energy and 4% produced renewable electricity. Importantly, we do not estimate any effect of the EU ETS on self-generation of either form of electricity suggesting that power purchase obligations are unlikely to be an important confounding source of variation. The estimated coefficients are small and statistically insignificant in all periods.

The results in Table B.7 also suggest that Feed-in tariffs for renewables and small combined heat and power (CHP) with up to 12 MW of capacity, introduced in , are also unlikely to have affected our identification of the EU ETS.[40] Therefore, while these other policies were important to the power sector (CRE, 2014), they do not seem to have differentially affected electricity generation at the manufacturing firms in our sample.

Electricity taxes To fund feed-in tariffs, the French government introduced the contribution au service public de l'électricité (CSPE) tax in January of 2003, which was levied on electricity consumption by firms and households. Therefore, the effect of this tax is comparable to any indirect treatment effects that may arise from the EU ETS. Our matching strategy results in matched pairs where the average difference in the share of electricity bought is a mere three percentage points. This should go a long way to control for effects arising from differential exposure to electricity prices and surcharges.

In addition, exemptions from the CSPE were granted for (i) metallurgical activities with chemical reduction or electrolysis, (ii) products for which the electricity cost represented more than half of the product cost, (iii) manufacturing of non-metallic mineral products, and (iv) electricity used in the context of energy production activities. These exemptions are limited to very electricity-intensive production processes. Their potential to confound abatement incentives under the ETS therefore is likely to be limited after matching on sector and the share of electricity that is purchased. We again note that there are no changes in emissions prior to the introduction of the ETS

[40] In Appendix C.2 we show that there is no association between the installation of a CHP plant or exploitation of renewable energy sources and participation in the EU ETS.

Table B.7: On-site Generation of Electricity

	Sources	
	(1) Thermal	(2) Renewable
Pre-Announcement	0.004	0.002
	(0.004)	(0.024)
Announcement	-0.010	-0.035
	(0.009)	(0.026)
Trading Phase I	0.002	0.023
	(0.016)	(0.039)
Trading Phase II	-0.008	0.056
	(0.020)	(0.041)
Mean in 2000	0.349	0.040
Observations	2,348	2,348

Notes: These estimates are the result of OLS regressions, estimated on a matched sample. Standard errors are clustered twoways: at the firm level and the matching group level. Each estimate reflects the difference between regulated firm and unregulated firm outcomes prior to implementation of the ETS and during Phase I and Phase II of the EU ETS. Each coefficient represents the difference relative to the year 2000. Means are reported for ETS firms in 2000. Units: . Significance levels are indicated as * 0.10 ** 0.05 *** 0.01.

when these taxes were introduced and restate that there was no change in the share of electricity that was purchased or self-generation of electricity, either prior to the EU ETS when the CPSE was introduced or after the EU ETS was implemented.

Fuel taxes Historically, excise taxes in France had been levied on petroleum-based fuels, and in particular on transportation fuel. Additional such taxes on coal, gas and fuel oil were introduced in 2006 and 2007 so as to comply with minimum taxes stipulated in EU Directive 2003/96/EC for the taxation of energy products and electricity. Callonnec (2009) provides an overview of the CO_2 price implicit in those excise taxes, finding that CO_2 produced by gasoline burning was heavily taxed at 265 euros per tonne vs. a nominal 6 euros per tonne of CO_2 from burning fuel oil and natural gas. Certain fossil fuels and specific applications were completely exempt, including coal used in industry as well as natural gas in a broad range of industrial applications (Callonnec, 2009). Due to low nominal levels of the tax and the broad exemptions granted in industrial uses, we have no reason to believe that they could confound ETS treatment effects when we match treated and control firms within sectors.

The French government also contemplated proposals to replace those excise taxes on fuels by a uniform tax on CO_2 by 2010, but such a tax was not implemented until long after the end of our sample period.

National energy efficiency plan Like other EU member states, France is required to design and implement measures conducive to meeting EU wide targets for energy efficiency improvements stipulated by the Energy Efficiency Directives.[41] Relevant to our study period is the first Energy Efficiency Action Plan (République Française, 2008). The plan stipulated a national energy savings target and devised sector specific measures for achieving that target. The focus was on sectors not included in the EU ETS, such as buildings, services, and transportation, because ETS sectors were already subject to an absolute emissions target implicit in the cap. Because of this, the plan contained only two measures targeting industry energy use.

Minimum efficiency levels were imposed for low-wattage boilers (4 kW to 400 kW) and for boilers with capacity between 400 kW and 50MW. In addition, operators of the latter category of boilers were required to put in place control devices for monitoring actual boiler efficiency and the combustion quality. Since this requirement applied equally to small and large boilers, we would not expect this policy instrument to have differential effects on treated and control firms. The same argument applies to a third feature, period inspections of thermal plants with a power greater than 1 MW. Designed to ensure compliance with minimum efficiency levels this policy instrument would apply to virtually all boilers in both the treatment and matched control group.

Standardization projects were coordinated nationwide by an energy management coordination group tasked with the definition of a common method for assessments and quality inspections of industrial energy management. The method "favours regular dialogue between the assessor and the industrialist during the assessment phases, which are an inventory of the company's overall energy situation, quantification of energy savings potential and definition of the actions needed for these energy savings." (République Française, 2008, p. 27).

It does not appear as though these measures were intended as stringent policies for curbing industrial emissions. Rather, the energy efficiency plan targeted energy use outside the industrial and energy sectors. In fact, only 1% of the total energy savings envisaged by the French energy efficiency action plan were contributed by the industrial sector, whereas the remaining 88% and 10% were expected to come from the residential and transportation sectors, respectively (République Française, 2011, p. 6).

We conclude that overlapping energy and climate policies in France were unlikely to be a first-order driver of the strong and robust estimated emissions reductions that we attribute to the EU ETS.

B.6 Firm Exit

The context of our study is a period of de-industrialization in France, as is reflected by the secular downward trend in CO_2 emissions. Between 2005 and 2012, the number of active manufacturing enterprises in France decreased by 5.9%, and this decrease was more pronounced in some sectors covered by the ETS.[42] This macroeconomic environment emphasizes the need to directly control

[41] See "Energy Services Directive" 2006/32/EC of the European Parliament and of the Council, of 5 April 2006, on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Also see "Energy Efficiency Directive" 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance.

[42] Eurostat – Structural Business Statistics, https://ec.europa.eu/eurostat/web/structural-business-statistics/database, accessed February 21, 2023. We thank an anony-

Table B.8: Firm Exit and ETS Participation

	Pr (Firm Exit)		
	(1)	(2)	(3)
Treated	-0.086**	0.002	0.049
	(0.029)	(0.032)	(0.033)
Sector Fixed Effects	No	Yes	Yes
Firm Size Control	No	No	Yes
Mean	0.397	0.397	0.397
Observations	3,262	3,262	3,262
R^2	0.002	0.111	0.122

Notes: This table reports coefficient estimates from a cross-sectional OLS regression. The dependent variable equals 1 for firms never observed after 2004 and zero otherwise. Sector fixed effects are at the SUPERNCE level (defined in 3). Robust standard errors are reported in parentheses. Significance levels are indicated as * 0.10, ** 0.05, *** 0.01.

for emissions reductions caused by structural change, so as to not misattribute them to the EU ETS. Analyzing the potential for differential firm exit, however, presents a number of empirical challenges. We need to be able to distinguish a firm exit from a merger or acquisition, as well as from sampling variation. Regarding identification, the parallel trends assumption needs to hold for exit rates.

Unfortunately, we are unable to directly examine firm exit. The raw data is an unbalanced sample of firms. Unfortunately, we do not know why firms drop out of our data. This may be due to firm exit, mergers, acquisitions, or due to sampling. This hampers our ability to conduct a rigorous analysis of exit. To address this we focus on a balanced sample of stayers in our main analysis. We restrict to firms that are observed at least once in each of the four periods. This minimizes the potential for bias that could arise as a result of differential firm survival. Focusing on stayer firms can account for firm exit, but it prevents us from investigating extensive-margin responses at the firm level as well as the contribution of firm exit to reductions in emissions. To explore the potential for this margin we investigate whether there is any differential attrition between regulated and unregulated firms after the introduction of the ETS.

Using the raw sample, we identify 3,262 firms that are (i) observed in the base year and (ii) have not exited before 2004. For those firms we construct a sample exit dummy that takes a value of one for firms never observed after 2004. Table B.8 reports the results of a cross-sectional OLS regression of this variable on the treatment indicator. Column 1 shows that ETS firms are less likely to exit than non-ETS firms. However, this correlation becomes much smaller and statistically insignificant after including sector fixed effects (column 2) and controls for firm size (column 3). These findings suggest that the ETS did not lead to systematically different exit patterns conditional on basic firm characteristics. As such, we conclude that our intensive margin analysis is unlikely to have substantially underestimated the effects of the EU ETS on emissions or economic

mous referee for suggesting this source to us.

performance.

C Abatement Investment and other Emissions Reducing Measures

Section 5 argues that the main mechanism driving our estimated reductions in emissions is the investment in new abatement capital. This appendix compiles more specific information on the nature of these investments from two datasets: (i) the Antipol survey introduced in Section 3, and (ii) data from telephone interviews with managers of French manufacturing firms.

C.1 The Antipol survey

The Annual Survey on Environmental Protection Studies and Investments (Antipol) is collected by INSEE. Metadata and questionnaires (in French) for recent years are available online.[43]

In our analysis of firm investments, we find evidence indicating that firms made substantial integrated investments (Table 3, column 6).

Integrated investments are defined as investments in "production tools to make them better performing in environmental terms than other equipment with similar functions and characteristics. This category includes equipment that generates less pollution compared to other tools available on the market (e.g. *acquisition of less polluting electric vehicles, less noisy machines, emitting less smoke, less greenhouse gases, generating less waste* [emphasis added]). Only the expenses dedicated to the abating pollution are taken into account here."

Since these examples are not very specific, we turn to an additional data source that is more suited to providing insights about specific measures and investments that firms may have made to abate emissions.

C.2 Emission-reducing measures as reported by managers

To complement our understanding of what investments firms made, we use qualitative data from a broad-based survey of managers at medium-sized European manufacturing firms. The data were collected by Martin et al. (2014) using a bias-reducing, "double-blind" telephone interview method developed by Bloom & van Reenen (2007). Participating firms were drawn at random from all mid-sized firms contained in a large commercial database (Bureau van Dijk, 2008). In France, 238 such firms were contacted between late August and October 2009, of which 140 were interviewed. Due to oversampling of EU ETS firms, 92 of the firms participate in the EU ETS. For a detailed description of the interview process and data collection, the reader is referred to Online Appendix A of Martin et al. (2014).

We focus on interview responses pertaining to measures that were implemented at the production site to reduce CO_2 emissions. Managers were asked "Can you tell me what measures you have adopted in order to reduce GHG emissions (or energy consumption) on this site? Have you bought any new equipment, or have you changed the way you produce?" Table C.1 summarizes these

[43] See https://www.insee.fr/fr/metadonnees/source/serie/s1232, last accessed on February 24, 2023.

Table C.1: Adoption of emissions reducing measures

	(1)	(2)	(3)	(4)
	All measures adopted		Most significant measure	
	Share of adopters (%)	ETS Firm	Share of adopters (%)	ETS Firm
I. Heating and cooling				
1. Optimized use of process heat	55	0.39***	19	0.16**
	(50)	(0.08)	(40)	(0.07)
2. Modernization of cooling /	6	-0.09*	1	-0.03
refrigeration system	(25)	(0.05)	(9)	(0.03)
3. Optimization of air	0	-0.02	-	
conditioning system	(8)	(0.02)		
4. Optimization of exhaust air	32	0.01	8	-0.01
system / district heating system	(47)	(0.08)	(26)	(0.05)
II. More climate-friendly energy generation on site				
1. Installation of CHP plant	9	0.08	8	0.07
	(29)	(0.04)	(26)	(0.04)
2. Biogas feed-in into local	0	-0.02	-	
CHP plant or domestic gas grid	(8)	(0.02)		
3. Switching to natural gas	20	0.06	9	-0.06
	(41)	(0.07)	(29)	(0.06)
4. Exploitation of	8	0.06	7	0.02
renewable energy source	(27)	(0.04)	(25)	(0.05)
III. Machinery				
1. Modernization of	15	0.10*	4	-0.02
compressed air system	(36)	(0.06)	(20)	(0.05)
2. Other industry-specific production	36	0.36**	17	0.16***
process optimization/machine upgrade	(48)	(0.07)	(37)	(0.06)
3. Production process	28	-0.12	12	-0.07
innovation	(45)	(0.08)	(32)	(0.07)
IV. Energy management				
1. Introduction of energy	10	-0.10*	2	0.02
management system	(30)	(0.06)	(13)	(0.02)
2. Submetering / upgrade of	21	-0.31	2	0.02
existing energy management system	(41)	(0.08)	(13)	(0.02)
3. (External) energy audit	10	0.03	-	
	(30)	(0.05)		
4. Installation of timers	12	-0.04	2	-0.02
attached to machinery	(33)	(0.06)	(13)	(0.03)
5. Installation of	6	0.02	1	
heating systems	(23)	(0.04)	(9)	
V. Other measures on production site				
1. Modernization of	31	-0.22**	4	-0.10*
lighting system	(47)	(0.09)	(20)	(0.05)
2. Energy-efficient site extension/	14	-0.05	1	-0.03
improved insulation/building management	(34)	(0.06)	(9)	(0.03)
3. Employee awareness campaigns	23	-0.03	2	-0.02
and staff trainings	(42)	(0.08)	(13)	(0.03)
4. Non-technical reorganization	1	-0.04	2	-0.05
of the production process	(15)	(0.03)	(13)	(0.04)
5. Installation of energy	2	-0.04	-	
efficient IT system	(15)	(0.03)		
6. Improved waste	24	-0.11	2	-0.05
management / recycling	(43)	(0.08)	(13)	(0.04)

Notes: Based on telephone interviews with managers of 140 French manufacturing firms, 92 of which were EU ETS participants in 2009. Columns (1) and (3) report the mean and standard deviation (in parentheses) of the adoption rate for a given measure. Columns (2) and (4) report the coefficient and robust standard error (in parentheses) on EU ETS participation in a linear regression of adoption on a participation dummy and a constant.

measures. Column 1 reports the percentage share of adopters for different measures, organized in five broad categories. The adoption rates highlight the importance of optimization processes targeted at heating, waste heat recovery, industry-specific processes or machinery, and lighting. Those measures were adopted by at least 30% of respondents and are consistent with sizeable potentials for waste heat recovery identified in the technical literature (cf. Ammar et al., 2012; Barma et al., 2017; Chowdhury et al., 2018).[44]

15%-30% of respondents reported adopting measures that include switching to natural gas, modernizing the compressed air system, innovating in the production processes, upgrading the energy management system, but also improving waste management and running employee awareness campaigns to reduce energy use.

We investigate how the adoption of these measures are associated with participation in the EU ETS. Column 2 reports the coefficient obtained in a linear regression of adoption on the ETS dummy and a constant. We estimate that participation in the EU ETS is associated with a higher likelihood of optimizing the use of process heat and the optimization of processes specific to their industry. By contrast, ETS participation is negatively associated with modernizing the lighting system.

Column 3 summarizes the adoption rates for the one measure that achieved the largest reduction in carbon emissions. Managers were asked: “Which one of these measures achieved the largest carbon saving?”, referring to the measures named in response to the previous question. This highlights once again the importance of optimizing the use of process heat for reducing carbon emissions and industry-specific machine upgrades or process optimization that are positively associated with EU ETS participation (reported in column 4).

We note that these correlations do not necessarily represent causal relationships. Together with our main results, however, they provide supporting evidence for the hypothesis that firms invested in new processes to reduce emissions.

D Attentive vs Inattentive Firms

In Section 5.3 we present results that suggest the effect of the EU ETS might be heterogenous across different firms due to differences in how informed or attentive firms are about the return to investments in clean energy technologies prior to the introduction of the EU ETS. We posit that firms with high TFP and low energy intensity – relative to industry medians – prior to the ETS, are are more likely to be informed and will already have taken advatnage of cost-saving opportunities. By contrast, firms with low TFP and high energy intensity may be more likely to have overlooked cost saving investments. The introduction of the ETS may have increased the salience of these opportunities now that the cost of carbon is focused. This may result in the realisation of relatively large emissions reductions alongside general efficiency improvements, offsetting the costs of the EU ETS and perhaps even reducing costs below their pre-ETS level.

Predictions are less clear for firms that are either low TFP and low energy intensity *or* high TFP and high energy intensity: a high TFP firm with high energy intensity could have high TFP either because of, or inspite of, using relatively large amounts of energy and therefore CO_2, e.g., high TFP could be the consequence of high capital intensity. However, it is also possible that

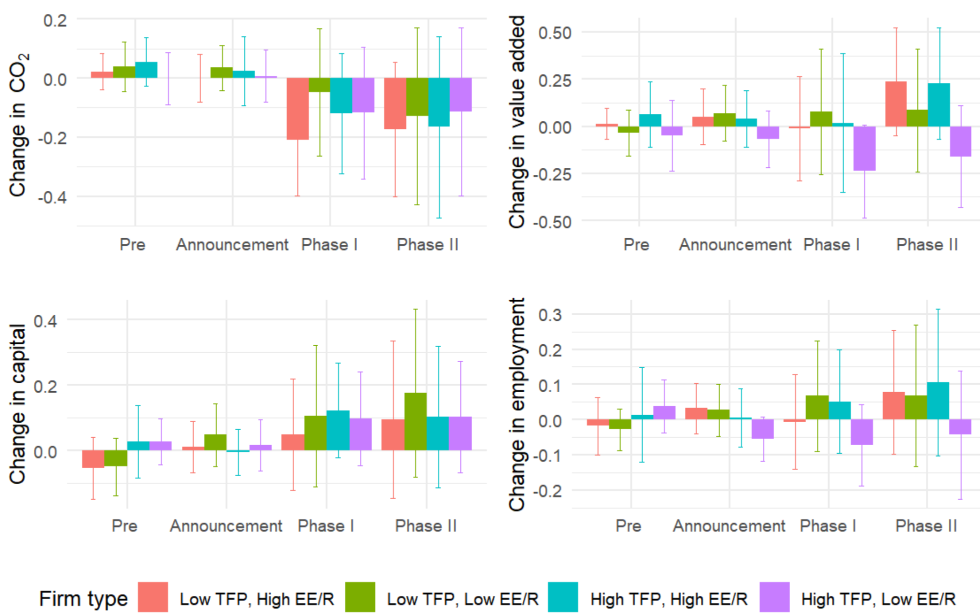
[44]We thank an anonymous referee for pointing us to this literature.

other factors were responsible for the success of the firm. In such cases, bandwidth constrained managers may have been pre-occupied with those other factors, e.g., developing the firms brand, resulting in less attention being paid to cost reduction opportunities in energy usage. In Figure D.1, we present results that are consistent with cost savings for high TFP, high energy intensity firms. We estimate emissions reductions alongside increases in value added and employment (although those estimates are not statistically significant at conventional levels.)

Similarly, for low TFP *and* low energy intensity firms, two opposing situations could apply: first, managers may have already deployed cost-saving energy reduction technologies, but overlooked other aspects of good practice contributing to their low TFP. Alternatively, both low productivity and low energy intensity could be due to lower general management capabilities. For instance, the firm might still rely on out-dated less capital intensive practices. The arrival of regulations that imposes further costs could lead to more widespread structural changes that lead to general efficiency improvements. The results in Figure D.1 are consistent with this latter narrative. We estimate reductions in emissions that are quantitatively smaller than the low TFP/High energy intensity group, alongside an increase in value added.

We only estimate negative value added and employment effects for the high TFP/low energy intensity group. This motivates our decision to define this group as "attentive" and the other three groups as "inattentive".

Figure D.1: Heterogeneity by initial TFP and energy intensity



Notes: The Figure reports regression coefficient (along with 95% confidence bands) of our main specification where we interact ETS by period effects with a classificaiton of firms into 4 groups according their RTFP and energy intensity, relative to their sectoral mean.

E Derivations and Calculations

E.1 Carbon Price Effect on Revenue TFP

Let w_E denote $\log(W_E)$. Abstracting from firm and time indices for simplicity, we can write the effect of the EU ETS on measured (revenue) TFP as

$$\begin{aligned}\frac{\partial \omega}{\partial w_E} &= \frac{\partial r}{\partial w_E} - \sum_{X\in\{E,M,L\}} s_X \frac{\partial x}{\partial w_E} - \left(\frac{\gamma}{\mu} - \sum_{X\in\{E,M,L\}} s_X\right)\frac{\partial k_{it}}{\partial w_E} \\ &= \frac{1}{\mu}\frac{\partial q}{\partial w_E} - \frac{\alpha_E}{\mu}\left(\frac{1}{\mu}\frac{\partial q}{\partial w_E} - 1\right) \\ &\quad - \sum_{X\in\{M,L\}} \frac{\alpha_X}{\mu^2}\frac{\partial q}{\partial w} - \left(\frac{\gamma - \sum_{X\in\{E,M,L\}}\alpha_X}{\mu}\right)\frac{1}{\mu}\frac{\partial q}{\partial w_E}\end{aligned} \tag{23}$$

where we have substituted $s_X = \frac{\alpha_X}{\mu}$, $\frac{\partial r}{\partial w_E} = \frac{1}{\mu}\frac{\partial q}{\partial w_E}$, $\frac{\partial e}{\partial w_E} = \frac{1}{\mu}\frac{\partial q}{\partial w_E} - 1$, $\frac{\partial e}{\partial w_E} = \frac{1}{\mu}\frac{\partial q}{\partial w_E}$, $\frac{\partial k}{\partial w_E} = \frac{1}{\mu}\frac{\partial q}{\partial w_E}$ using equations (7), (5), and the factor share identity (10). Taking logs of equation (6) and taking the partial derivative yields $\frac{\partial q}{\partial w_E} = -\frac{\alpha_E \mu}{\mu - \gamma}$ which we substitute into (23) to get

$$\begin{aligned}\frac{\partial \omega}{\partial w_E} &= \frac{1}{\mu}\left[\left(1 - \frac{\alpha_E}{\mu} - \sum_{X\in\{M,L\}}\frac{\alpha_X}{\mu} - \frac{\gamma - \sum_{X\in\{E,M,L\}}\alpha_X}{\mu}\right)\frac{\partial q}{\partial w_E} + \alpha_E\right] \\ &= \frac{1}{\mu}\left[\left(1 - \frac{\gamma}{\mu}\right)\frac{\partial q_{it}}{\partial w_{Eit}} + \alpha_E\right] = -\left[1 - \frac{\gamma}{\mu}\right]\frac{\alpha_E}{\mu - \gamma} + \frac{\alpha_E}{\mu} = 0\end{aligned}$$

E.2 Aggregate Effects of the EU ETS

Our objective is to understand the contribution of the EU ETS to aggregate emission reductions during the period of analysis. For consistency, we construct aggregate emissions from our microdata. As with our main analysis we do not speak to process emissions. Let the variable CO_2 denote aggregate industrial combustion emissions in France. This variable is plotted as a black line in Figure 1.

Because we construct the aggregate from the micro-data we have aggregate ETS and non-ETS emissions. This allows us to construct counterfactual aggregate emissions for ETS firms had they not been regulated. We do this using our matched-sample difference-in-differences estimates from Table 1 as follows:

$$\widehat{CO_2}(t)^{NoETS} = CO_2(t) - CO_2(2000) \cdot \left(\sum_{\tau=1}^{4} \beta_\tau \cdot \mathbf{1}\{t \in \Phi_\tau\}\right)$$

where Φ_τ are the treatment phases defined in Section 2.2. Since only the point estimates for Phase I and Phase II are statistically significant, we let $\beta_4 = \hat{\beta}_4$, $\beta_3 = \hat{\beta}_3$ and $\beta_1 = \beta_2 = 0$. The variable $\widehat{CO_2}(t)^{NoETS}$ is plotted as a dark gray line in Figure 4. We calculate that annual aggregate emissions would have been 5.4 million tonnes higher on average between 2005-2012 if the EU ETS did not exist.

In addition to calculating how much higher emissions would have been absent the EU ETS, we also calculate the contribution of the EU ETS to the aggregate decline in emissions observed since the ETS went into effect.

We consider two benchmarks to evaluate the contribution of the ETS to aggregate emissions reductions. First we use emissions in 2004 (the dashed line in Figure 4). As an alternative benchmark we estimate the linear trend in emissions prior to the EU ETS and extrapolate this trend going forward.

Using these two benchmarks we calculate the difference between observed emissions and the benchmarks to get an estimate of the overall change in emissions following the introduction of the EU ETS. The overall reduction in emissions comprises not only the treatment effect of the EU ETS but also the effects of concurrent shocks that may have affected industrial emissions, such as the Great Recession, concurrent policies, and technical change.

To evaluate the relative contribution of the EU ETS to the overall reduction in emissions during this period, we calculate the average difference in emissions, using the following ratio,

$$\frac{\frac{1}{t}\sum_{t=1}^{T}[\widehat{CO_2}(t)^{NoETS} - CO_2(t)]}{\frac{1}{T}\sum_{t=1}^{T}[CO_2(2004) - CO_2(t)]}.$$

We calculate that on average approximately 27% of observed emission reductions between 2005 and 2012 can be attributed to the EU ETS using 2004 emissions as a benchmark. Using the linear trend in pre-ETS emissions, we calculate that on average approximately 47% of the of the observed emissions reductions between 2005 and 2012 can be attributed to the EU ETS. While these are non-trivial shares, this highlights the need for causal research designs when evaluating the efficacy of climate policy. Extrapolating aggregate trends to draw inferences would vastly overestimate the contribution of the EU ETS as a driver of aggregate emissions reductions.

Table E.1 presents the data underlying Figure 4, as well as annual differences and contributions for the two benchmark comparisons.

Table E.1: The Contribution of the EU ETS to Aggregate Emissions

Year	Aggregate Emissions	Aggregate Emissions (No ETS)	Difference	Contribution (2004 Benchmark)	Contribution (Linear Trend Benchmark)
1996	94.863	94.863	–	–	–
1997	95.534	95.534	–	–	–
1998	98.477	98.477	–	–	–
1999	98.187	98.187	–	–	–
2000	94.436	94.436	–	–	–
2001	91.180	91.180	–	–	–
2002	86.834	86.834	–	–	–
2003	83.874	83.874	–	–	–
2004	85.392	85.392	–	–	–
2005	72.057	78.243	6.186	0.463	0.541
2006	73.118	78.979	5.861	0.478	0.677
2007	72.505	78.313	5.808	0.451	0.769
2008	69.928	76.505	6.577	0.425	0.782
2009	57.341	64.108	6.767	0.241	0.351
2010	60.674	64.665	3.991	0.161	0.280
2011	57.159	61.168	4.009	0.141	0.250
2012	65.061	69.244	4.183	0.205	0.654

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