ESSAYS ON FIRMS' BEHAVIORS IN THE EUROPEAN UNION EMISSION TRADING SCHEME (EU ETS)

A Dissertation

Submitted to the Faculty

of

Purdue University

by

Yifei Xu

In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

August 2020

Purdue University

West Lafayette, Indiana

THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF DISSERTATION APPROVAL

Dr. Chong Xiang, Chair

Krannert School of Management

Dr. Dominique Y van der Mensbrugghe

College of Agriculture

Dr. Anson Soderbery

Krannert School of Management

Dr. Farid Farrokhi

Krannert School of Management

Approved by:

Dr. Brian A. Roberson

Head of the School Graduate Program

For my dad Jianzhong, mom Xiaohong, and husband Woohyung

ACKNOWLEDGMENTS

I would like to express my special appreciation to my my Ph.D advisor, Prof. Chong Xiang, who not only diligently guided me through the development of this thesis, but also encouraged me whenever I was struggling in darkness with the difficulties during my research. I feel really grateful for all his help, advice and encouragement during my graduate study.

I am very appreciative towards Prof. Dominique Y van der Mensbrugghe, who not only helpfully connected me to people and resources that benefit for my research, but he were also very supportive and helpful regarding my after-Ph.D life.

I am especially indebted to Prof. Pengfei Liu for becoming the Associate Advisor of my thesis at the time when I was struggling in darkness with the third chapter. Without his help, it is unlikely that this chapter would have ever been written.

At various points during the development of this thesis, I benefited from suggestions and advice from several faculty members in my committee. In particular, I am very thankful to Prof. Anson Soderbery and Prof. Farid Farrokhi.

I am very appreciative towards Prof. Calel Raphael, who, during my SEA conference in Washington D.C., patiently discussed a draft which later became the first chapter of my thesis. These discussions also gave rise to an idea which was then developed into the third chapter of this thesis.

I am thankful to the administrative staff of the Department of Economics at Purdue University for their professionalism, company and friendship during these years. I would like to thank my fellow graduate students who shared the happiness and sorrow during the PhD years. I am especially grateful to Karen Zhong, Svetlana Beilfuss and Mintao Xu, for their friendship and moral support.

Lastly, but not least, I want to thank my parents, husband for bearing with me through the rush of the past year, for their kindness, love and faith in me.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Xu, Yifei Ph.D., Purdue University, August 2020. Essays on Firms' Behaviors in the European Union Emission Trading Scheme (EU ETS). Major Professor: Chong Xiang.

This dissertation consists of three chapters about the European Union Emissions Trading Scheme (EU ETS). All chapters contributes to the scarce but recently great-developing literature on installation and firm-level studies in the EU ETS. The first chapter evaluates the policy effectiveness and efficiency by theoretical modelling and empirical assessment of firms' emission abatement activities. The second chapter overviews the global emission trading market, documents the institutional background of emission trading, and analyzes firms' emission trading patterns in light of the broader empirical literature. The last chapter studies productivity and firms' emission permit trading behaviors by considering a complete set of options.

In the first chapter, I investigate how firms reduce emissions under continuous adjustment of the policy by using the implementation of the three phases of EU ETS as a cost shock. I develop a model of emission abatement with heterogeneous firms by introducing two channels: *Reallocation* and *Investment* which incur variable and fixed abatement costs respectively. More productive firms are cleaner as they put more effort on *Investment*. However, the policy effect is ambiguous driven by the magnitude and correlation of the proposed abatement technology parameters, which highlights the importance of the current abatement technology for firms' responses to climate policy. I then empirically test the model by using a novel dataset that matches firms' financial, production and emission data. In addition to providing the elasticity of emission intensity, the elasticity of *Reallocation* and *Investment*, the model enabled me to estimate the firm's abatement technology parameters and decompose the emissions into the proposed two channels. The results indicate that firms have a higher efficiency

on abatement in utilizing of inputs than green technology investment. The emission change is primarily driven by the channel of *Reallocation* and is concentrated in non-metallic mineral companies. The green innovation is limited under the policy with a small emission intensity decrease even though there is large emission reductions.

The second chapter reviews the global rise of emission trading, documents the institutional background of emission trading, and summarizes firms' emission trading patterns. To the best of my knowledge, this study is one of the first to empirically analyze the trading behaviors of all ETS firms covering all three phases in the EU ETS. I use two micro-level datasets to investigate the permit trading behaviors of all types of trading in the market, including international offset permits. Some explanations of the identified trading patterns are provided in this paper. Additionally, this study also discusses the patterns in light of the broader empirical literature.

The last chapter contributes to the literature on the firms' permit trading behaviors. The development of the EU ETS has complicated firms' decisions around carbon trading and offered firms more options to offset emissions. We provide a first look at the determinants behind firms' participation in the EU ETS as well as their trading behaviors by considering a complete portfolio of permit trade markets in the EU ETS. Based on a comprehensive permit transaction dataset linked with individual level firm's characteristics, we quantitatively analyze firms' participation decisions and trading patterns. We focus on the impact of firms' productivity, endowment position, and endowment value on market choice and trading amount. Our results suggest that productive firms are more likely to participate in permits trading and to purchase the permits in the secondary and international markets. Conditional on firms' market choice, the permit trading amount is also correlated with a firm's productivity and endowment value. In addition, firms in power and energy sector are more likely to participate in permit trading than other manufacturing firms. Overall, the empirical results indicate that less productive firms have disadvantages competing in the permit trade market.

1. THE IMPACT OF THE EU ETS ON REGULATED FIRMS: ABATEMENT ACTIVITIES IN MANUFACTURING SECTORS

1.1 Introduction

Cap-and-trade is the most popular way to regulate greenhouse gas (GHG) emissions worldwide. It functions as the main instrument for climate change policy, which captured both policy makers' and researchers' attention. The European Union Emission Trading Scheme (EU ETS) operates the first and largest GHG cap-and-trade scheme in the world. It launched in 2005, regulating more than 15000 power and industrial plants in 31 countries, accounting for over 45% of the EU's total greenhouse gas emissions. In addition to improving the way countries promote their ecological sustainability, the EU ETS can also work as a tool of economic development. In specific, the EU ETS stimulates innovation in the emerging European low-carbon economy and makes regulated firms more competitive internationally through providing incentives for low-carbon innovation (Anderson et al., 2011; Martin et al., 2013; Calel and Dechezlepretre, 2016). Like all of the new emissions trading initiatives around the globe, the aim of the EU ETS is to reduce carbon emissions, but to do so through low-carbon innovation rather than output reduction. Regarding whether the EU ETS is accelerating the goals, the carbon market in general and the EU ETS in particular have been much debated. Especially, the system that was implemented has been under ongoing discussion on how to reform it. The purpose of this paper is to provide comprehensive evidence for this ongoing debate by investigating the impact of the EU ETS on carbon emissions focusing on firms' abatement activities.

A large body of work evaluating the impact of the EU ETS on environmental performance focuses its impact on countries and industries. In other words, most research considers the effectiveness of the EU ETS on a macro level (Ellerman et al., 2010; Egenhofer et al., 2011; Kettner et al., 2013). As pointed by Levinson and Taylor (2008), "Macro level data does not allow researchers to distinguish between the production facilities that are regulated or exempt under the particular policy being evaluated." Therefore, these papers do not address the issue of aggregation bias. Given that firms are the main emission generators and different in many aspects, it is essential to explain the mechanisms underlying the aggregate emission level findings by considering firms' heterogeneity in abatement activities. Once one has taken into account the different forms of abatement activities and firms' heterogeneity, there are important questions constantly coming up for discussion. For instance, what are firms' abatement technologies, and how efficient are they? What fraction of emission reduction is explained by each identified abatement activity? How do competitive firms differ in terms of abatement activities and emission intensity? How do firms' abatement activities change under the adjustment of the EU ETS?

This paper takes the first step in answering these questions. A model of emission abatement with heterogeneous firms is developed. The model follows the tradition of Copeland and Taylor (2005) in that emission can be treated as a byproduct, as well as an input of production. The implementation of three phases of EU ETS is interpreted as a cost shock. From there, I propose two channels by which firms may reduce emission effectively: *Reallocation* and *Investment*. The two channels represent two intuitive premises in the literature (Kozluk and Zipperer, 2015). According to a more traditional approach, environmental policy hampers productivity. Higher policy compliance costs could, for example, crowd out productive investment in innovation or efficiency improvements and slow down productivity growth. This burden on economic activity approach is explained by *Reallocation*. In contrast, the Porter Hypothesis claims that innovation could grow alongside environmental policy by encouraging the development of low-carbon technologies. The gains in productivity could, according to the hypothesis, outweigh the costs of the policy. The *Investment* channel considers how innovation is thus able to thrive without damaging productivity.

My model decomposes the emission intensity into the aforementioned channels of *Reallocation* and *Investment*. Furthermore, it quantifies the contribution of each abatement channel under adjustments of the EU ETS during three phases. It connects two different abatement activities together and provides a way to do joint effects analysis. The model makes each factor's contribution to environmental performance clearer given a tight mapping from model to empirics. It allows me to estimate firms' abatement technology parameters: *reallocating elasticity*, which captures how efficient the firms are in terms of using inputs; and *green elasticity*, which measures how efficient the firms are in terms of technology investment. These abatement technology parameters are important in the sense that they provide specific information on firms' current production and abatement technology efficiency. To develop and adjust future policy around the goals of the EU ETS, we must know the quality of the current abatement technology and have a sense of the future green technology innovation potential.

The model predictions are demonstrated empirically through constructed firm-level panel data during an EU ETS regulation period. I matched firms' emission data from World Carbon Market database with the firms' production and financial information from Bureau van Dijk Amadeus database. The data patterns reveal further evidence on firms' abatement activities and their heterogeneous emission levels. The regression results are consistent with my model predictions. The theoretical and empirical results provide the following new perspectives.

First, more stringent policy may lead to less low-carbon investment. Because the emission is treated as a production input in the model set up, more stringent policies result in higher operating and production costs. When the input is lower, so are emissions. Since the overall emissions reduce through output sacrifice, firms would like to put less effort on reducing emissions through low-carbon investment. We could also observe a consistent result from the data when we make the tangible fixed asset as a proxy for abatement investment following the literature (aus dem Moore et al., 2019).

Second, the policy has an ambiguous net effect on emission intensity, depending on which abatement activity's effect is dominant. This fact is mainly related to firms' current abatement technologies. The ambiguous net effect of policy stringency on emission intensity highlights the importance of firms' responses to climate policy. In addition, when taking account of policy effect on cleaner production, it is essential to understand the efficiency of current abatement technology in different types of abatement activities.

Third, the abatement technology parameters reveal emission abatement potential under the policy. Specifically, policy effects on *Reallocation* and *Investment* activities move in opposite directions in the model. As a result, whether or not the policy is encouraging cleaner production depends on the magnitude and correlation of the proposed abatement technology parameters. According to the estimation of the abatement technology parameters, firms' reallocation efficiency is much higher than the investment efficiency, which indicates that policy leads to lower emission intensity based on the fact that firms have a higher efficiency in their use of inputs than in their use of low-carbon technology investment.

Fourth, the decomposition of emission intensity into two channels shed light on the efficiency of the policy on cleaner production. *Reallocation* represents a channel of production sacrifice and *Investment* captures low-carbon technology adoption. The estimates suggest that there is a small emission intensity decrease even though there were large emission reductions due to *Reallocation* channel. The overall emission reduction does not imply cleaner production but emission intensity does. Therefore, the efficiency of the EU ETS for its long-term goal of cleaner production is limited.

I now further clarify how this study complements previous work and contributes to the literature. It makes contributions towards two general directions: theory and empiric. Regarding the paper's theoretical contribution to the field, first, my emission abatement model that considers heterogeneous firms through *Reallocation* and

Investment contributes to the growing literature on heterogeneous firms and their environmental performance. Most of the previous studies are based on the Melitz (2003) model in the trade literature. Cui et al. (2012), Holladay (2016), and Forslid et al. (2018) all show that exporters are more productive and generate lower emission intensity compared to less productive non-exporters. They highlight how trade liberalization leads to cleaner production through one type of abatement activity. In contrast, this study emphasizes the effect of environmental policy by looking at the relationship between productivity and two types of abatement activities as it is affected by *Reallocation* and *Investment*. The direct cost shock of environmental policy is implemented in this paper; however, there is no event study of trade shocks during the period covered in above listed papers. Therefore, earlier studies may not accurately identify variation. This study solves this problem by introducing cost shocks and policy adjustments as needed.

Second, the model extends the basic model of trade and environment from the Copeland and Taylor (2005) by introducing two abatement activities in their general form of abatement function. The model is more in line with Cao et al. (2016). They study firm investment in abatement technology under a heterogeneous firm framework by emphasizing that firms' abatement investments exhibit an inverted U-shape with respect to productivity level. On the contrary, I show that the firms' abatement investment is positively related to firms' productivity and furthermore confirm it with data patterns within the EU ETS regulated firms. My study is based on CES preference, which is consistent with most studies in the literature (Konishi and Tarui, 2015; Anouliès, 2017; Forslid et al., 2018). The theoretical framework in this paper predicts that firms with higher productivity have lower emission intensity. This negative relationship between emission intensity and productivity is confirmed by a number of empirical studies in different countries. Studies focus on US manufacturing industry such as Shadbegian and Gray (2003) and Cui et al. (2012) and works look at Chinese manufacturing industry such as Earnhart and Lizal (2010). Forslid et al. (2018) also verify this relationship by using Swedish firm level data.

This paper furthermore contributes to a number of studies that examine the effects of environmental policy that incorporates firm level heterogeneity. Lots of studies look at the impact of carbon tax based on the simulation analysis. Yokoo (2009) finds that, under more stringent regulations, resources are aggressively reallocated to more productive firms; Cao et al. (2016) point out the different incentives to invest in abatement technology across firms driven by tighter carbon tax. Few studies theoretically evaluate the cap-and-trade policy that incorporates firm heterogeneity in abatement activities. Sartzetakis (1997), Newell and Stavins (2003), and Goulder and Parry (2008) consider heterogeneity in a cap and trade framework by generally looking at the effect of heterogeneity in emission abatement costs. Their focus is the comparison between the emission trading and the command-and-control regulations. They suggest that the cost saving of the emission trading is greater than the one of command-and-control regulations. These studies abstract away from specifying firms' abatement channels, as well as any abatement technologies. My paper models firms' endogenous choice between two abatement activities, which results in heterogeneous emission abatement costs. I do not compare the policy instruments relying on experiments but instead verify the predictions through empirical data.

Through empirical works, my study contributes to a branch of firm level studies that examine the impact of the EU ETS on environmental performance (Ellerman and McGuinness, 2008; Delarue et al., 2010; Dechezleprêtre et al., 2018). Most previous studies use diff-in-diff method and find a causal impact of the EU ETS on emission reductions of regulated firms from several countries. They are unable to identify the channels of their findings and call for further research to explore the drivers of emission abatement. They emphasize that it is crucial to understand the mechanisms through which facilities abate for better policy design and amendment. My paper tends to fill in this gap by identifying and quantifying two types of abatement activities. Some studies provide evidence for firms' current abatement activities including promoted $R\&D$ activities, low-carbon patent applications, as well as resources relocation (Calel, 2018; aus dem Moore et al., 2019). Different from these studies that only focus on one single channel, this paper combines two general forms of abatement activities in line with their revealed current abatement technologies. I mainly focus on firms' endogenous choice between them, which highlights the importance of firms' heterogeneity in understanding the performance and efficiency of the EU ETS.

There are some papers identifying and proposing different channels of emission abatement under the policy. However, to my best knowledge, few studies estimate the abatement technology efficiency in manufacturing industry due to the following reasons: it is hard to identify and separate different efficiencies; and abatement activities and technologies are more complicated in manufacturing sectors than power and transportation sectors. I introduce two channels in the model and estimate the corresponding abatement technology parameters. As a consequence, this study connects to a vast literature in Industrial Organization, including estimating production function and markup (De Loecker and Warzynski, 2012; Dobbelaere and Mairesse, 2013; De Loecker et al., 2016). Most importantly, it also adds to the studies of estimating abatement technology efficiency. A lot of works narrow down to one specific pollution or sector (Reinhard et al., 1999; Hailu and Veeman, 2000; Isaksson, 2005). For instance, Cofala and Syri (1998) investigate the abatement technology for controlling SO_2 emissions. Their methodology is illustrated by two examples for typical control technologies, wet flue gas desulfurization, and the use of low-sulfur gas oil. Otto and Reilly (2008) examine abatement technology in power sector by highlighting the effectiveness of CO_2 capture and storage (CCS). Different efficiencies are demonstrated under different combinations of policies including emission trading. Due to the complexity of specific abatement technologies in firm level, I first propose the abatement activities in more general forms representing firms' efficiency in use of inputs or in use of investment. I then estimate these two firms' abatement technology parameters in manufacturing sectors.

There needs to be an accurate measure of environmental stringency to better evaluate the impact of the policy. This is a difficult task due to the complex nature of environmental regulation (Brunel and Levinson, 2016). In regards to the EU ETS specifically, the previous studies, such as Chan et al. (2013), Veith et al. (2009), and Anderson et al. (2011), take the market carbon trading price as a measure of the EU ETS stringency, assuming all regulated firms are facing the same marginal compliance cost, which excludes the potential impact of caps and free allocated allowances. For example, rather than paying for emissions released, a firm that gets an emission permit surplus can generate revenue by selling extraneous permits or could face non-compliance costs by banking the extra permits. The ignorance of cap and endowment based policy stringency variation among firms would lead to measurement bias. The concerns of measuring the EU ETS stringency by only considering the carbon trading prices are alleviated by taking account of the special exemption of free endowments and penalties in my study (Goulder and Parry, 2008; aus dem Moore et al., 2019).[1] It provides a more complete and precise compliance cost estimation. Specifically, by combining the information on caps, free allowances, and the penalties over time, a policy stringency indicator is constructed to assist the model as a compliance cost shock.

The remainder of the paper proceeds as follows. Section 2 outlines the two sources of the data and describes the summary statistics. Section 3 reports the key data patterns. Section 4 spells out the model and derives the model predictions. Section 5 draws out empirical design and obtains the values of production parameters. Section 6 presents the results and discusses the findings in light of the broader empirical literature. Section 7 concludes by considering some of the potential policy implications, and directions for future research.

1.2 Data and Descriptive Statistics

I combine two principal sources of data into matched firm-level data suitable for investigating heterogeneous abatement activities under the regulation. The first data

[1] Goulder and Parry (2008) state that the toolkit of environmental instruments includes emissions taxes as well as tradable emissions allowances. aus dem Moore et al. (2019) suggest that as fewer and fewer emission allowances are allocated for free, the effect of the EU ETS on emissions should increase.

source is a firm-level emission data from the World Carbon Market Database, which is a unique information platform on the world's carbon trading markets. The advantage of this dataset compared to the European Union Transaction Log (EUTL) is that it aggregates regulated installations' emission and free allowance into a firm level. Thus, it identifies firms in Europe that are regulated by the EU ETS.[2] It also provides firms' BvD identifier that can be directly matched to the Bureau van Dijk Amadeus dataset. In addition, the data includes firms' detailed geographical information such as region, city, street, building, zip code, and phone number. Another data source offering novel information on firms' production and financial statement is Amadeus data from the Bureau van Dijk database. The Amadeus covers all firms in Europe including small private firms. It presents firms' production information such as sales, profit, employment, production cost, value added, and export turnover, as well as the detailed geographical information.

After matching the above two datasets together, a final merged sample results in an unbalanced panel from 2005 to 2016 of a number of 3186 firms. Table 1.1 presents summary statistics of the main variables of interest in the matched data. In studying firms' environmental performance, data on carbon emissions is of particular use. First, it is a direct measure of installation level of actual emissions, not an estimation based on energy use. Second, the emissions data are verified and audited every year by accredited carbon verifiers such as DNV, SGS, and Bureau Veritas. Therefore, it is a trusted data source for professional use. It solves the issues of inaccuracy and unreliability by using self-reported data produced on a voluntary basis. In order to measure emission adjustment controlling for production, emission intensity, calculated by emission over operation revenue, is used as the main variable of interest. On average, each firm's emission intensity is 0.41 ton CO_2 per euro value of production.

The matched data contains information at the firm level for a large number of variables. This paper also focuses on information on firms' tangible fixed assets, rev-

[2]Firm that operates at least one EU ETS-regulated installation identified as the regulated firm.

enue, employment, capital, and material. On average, an EU ETS-regulated firm spends large amounts of money on material. This is not surprising because the regulated firms are energy and carbon intensive. The firm's productivity is measured by total factor productivity, which is calculated from estimates of productivity functions using the method by Ackerberg et al. (2015). The policy stringency is a constructed policy indicator combining information of caps, allowances, EUR permit prices, and penalties. More details are discussed in Section 5.

1.3 Data Patterns

In this section, the main data patterns and empirical findings of selected manufacturing sectors are being presented.[3] First, the data indicates that the adjustments in firms' emissions during the three phases of the EU ETS can be explained by emission changes due to continued installations. It has little to do with the way installations enter and exit emissions statuses. Installations can be aggregated into firm level; therefore, the aggregated emission adjustment is mainly driven by emission changes from continued firms. Second, the data patterns show the descriptive evidence on firms' verified emissions and illustrate the potential drivers of the emission intensity. Specifically, for regulated firms, higher levels of tangible fixed assets correspond ceteris paribus to lower levels of emissions. More productive firms are more environmental friendly. Additionally, it demonstrates how policies vary among sectors and how allowances and emissions correlate over time. These data patterns motivate the model in Section 4, and the details are described as follow.

DATA PATTERN 1: *Extensive margin plays a relatively small role in emission adjustment under the EU ETS as a whole; however, it becomes more and more important across phases.*

[3] Selected manufacturing sectors: Non-metallic Minerals, Pulp and Paper, Petroleum and Coke, Basic Metals, and Chemicals. Together, these five sectors account for 92% of the aggregate emissions of the EU ETS manufacturing industries, and 30% of the overall emissions of the EU ETS.

Given the emission declines under the EU ETS over time, I first evaluate what fraction of the decline is explained by installation entry and exit into and out of the operating status and similarly what fraction is explained by the emission changes of the continuing operating bundle. Figure 1.1 shows the emission adjustment decomposition from 2005 to 2016. It demonstrates the breakdown of aggregate movements in emissions by total, extensive, and intensive margins yearly. Note that the sum of extensive and intensive margins lines equals the growth rate of aggregate emissions, which is represented by *Total* line. They plot the share of overall emission adjustment based on each margin, not the adjustment of each margin, and therefore correspond to the economic significance of each type of adjustment. The data displays that the extensive margin, defined as the entry and exit of installations, plays a small role in understanding emission adjustment during the EU ETS. It becomes obvious that emission adjustment under the EU ETS is mostly driven by the intensive margin: emission abatement within installations simultaneously. For example, the *Intensive* line dips to about -9% in 2009, while the *Extensive* line reaches to about -0.5% only. This means that while overall emissions declined by nearly 9.5% in 2009 compared to 2008, the vast majority came from the intensive margin. Although in terms of margins, these entries and exits explain only a small fraction of the decline in emission overall, their effect becomes more and more prominent across phases of the EU ETS. For instance, the *Extensive* line becomes more volatile after 2008. This pattern extends the findings in the literature to characterize a large emission adjustment of the manufacturing sector during the EU ETS.

DATA PATTERN 2: *Emission reduction due to the EU ETS varies with firm size, and emissions of big firms decline less than those of small firms.*

Figure 1.2 specifies the pattern of emission adjustment by firms' characteristics. The amount of emission reduction between phases I and III varies with firm size. Here, I use firms' initial emission amount to proxy the firm size.[4] The matched

[4]My proxies follow Calel and Dechezlepretre (2016) who use emissions and initial permit endowment to proxy firm size.

sample divides firms into percentiles based on the size of their emissions in phase I. The trend increases, which means the change of emissions from phase I to phase III becomes less negative as one moves from the smallest firms on the left to the larger firms on the right. It indicates that the largest buckets of production had the smallest magnitude declines in their emissions from phase I to phase III. To look into what drives this pattern, I focus on the characteristics of the installations within a firm. I notice that it is explained in part by the relatively greater share of old carbon-intensive installations, which belongs to smaller firms that exit production. More generally, the data pattern shows the variations of firms' emission reduction under the policy shock. The firm size is one of the firms' characteristics. Besides the firm size, it motivates me to look into what other factors and how these factors drive the heterogeneous emission abatement behaviors.

DATA PATTERN 3: *Firms with higher tangible fixed assets have lower emission intensity.*

According to the data, while tangible fixed assets and verified emissions exhibit a positive correlation, significant movement of firms' emissions between phase I and phase II, phase II and phase III suggests that abatement efforts might have taken place. Furthermore, emissions are strongly correlated with economic activity and thus are subject to external shocks, such as the financial crisis of 2008.

Table 1.2 shows the results of a two-way fixed effects regression of tangible fixed assets in logs on verified emissions in logs for the regulated period of the EU ETS (2005-2016). Once operating revenue is taken into account, the coefficient for tangible fixed assets remains negative and highly significant. Although the coefficient of tangible fixed assets is small compared to operating revenue, it indicates that for regulated firms, higher levels of tangible fixed assets correspond ceteris paribus to lower levels of emissions. Since firm size effects and yearly shocks are explicitly controlled for, this suggests that the asset value of low carbon production technology has been higher than the value of emissions-intensive technology. Thus, an increase in fixed assets by regulated companies from 2005 to 2016 may capture abatement investment reasonably well.

In order to provide a clearer evidence, the correlation between the firm's emission intensity and tangible fixed assets is shown by sectors. Figure 1.3 demonstrates the data pattern that, the more investment there is in tangible fixed assets, the lower the emission intensity. It indicates one potential channel through which firms are abating.

DATA PATTERN 4: *Firms with higher productivity have lower emission intensity.*

Figure 1.4 demonstrates how firm-level emissions per output vary with productivity. For most sectors such as pulp and paper, chemicals, non-metalic minerals, and basic metals, productivity is negatively correlated with the emission intensity. Thus, the more productive firms are cleaner, which is an important property of the proposed model. More productive firms in the model are cleaner because they invest more in abatement. Figure 1.4 shows that the model prediction is well established depending on the data pattern.

DATA PATTERN 5: *There is a parallel movement of emission with allowance over time, and it varies among sectors.*

As discussed in Branger et al. (2015), emissions trading is complicated by differences in sectoral coverage and exemption rules, such as differences in free allowance allocation provisions, which not only affect the level of policy stringency, but also alter incentives and influence the behavior of firms. Therefore, it is crucial to understand how emission is correlated with the allowance allocation over time. It is for better measuring the policy stringency as well.

Figure 1.5 plots the average log value of emissions and the log value of allowances with the variance over regulated time. It displays the correlation between allowances and emissions, especially tight in the pulp and paper, and chemicals sectors. Most importantly, variations in policy stringency arise due to the way allowance allocations vary across sectors and the allowance movements vary over time. For example, as stated in Figure 1.5, in the pulp and paper sector, firms' emissions decrease over regulated phases so as the allocated allowances. However, in chemicals sector, firms' emissions tend to increase over phases as a result of the expanded allowances allocation.

1.4 A Model of Emission Abatement with Heterogeneous Firms

In this section I develop a model of emission intensity with heterogeneous firms and illustrate the intuition of key abatement technology parameters. A key feature of the model is that heterogeneous firms reduce emissions over the EU ETS regulated periods by optimally choosing between two activities: fixed abatement investment and primary factor of production reallocating. More specifically, firms that are productive enough to set up production make decisions: whether to reduce emissions through investment that incurs fixed abatement costs or reallocating the primary factor of production that incurs variable abatement costs; and how much to invest or reallocate in order to get along with the policy. These two decisions are subject to production costs and emission compliance costs.

1.4.1 Model Setting

Production Structure

Consider a firm, indexed by i, producing an industrial output q using primary inputs labor L and capital K. Each firm has a TFP given by A, which is the firm's exogenous technology. In the tradition of Copeland and Taylor (2004), a firm can divert a fraction of the primary factor, labor and capital, away from the production of q to emission abatement. The effort in emission control diverts resources away from production, which is consistent with environmental regulation hampering productivity. Consider γ as a variable abatement cost that is determined by each firm in order to maximize profit. The fraction of primary factors available for production is $1-\gamma$ and the industrial output the firm produces is

$$q_i = (1-\gamma_i)A_i L_i^{1-\mu} K_i^{\mu}. \tag{1.1}$$

At the same time, the environmental emission e generated from the firm's production is as follows:

$$e_i = \Theta(\gamma_i, f_i)A_i L_i^{1-\mu} K_i^{\mu}. \tag{1.2}$$

$\Theta(\gamma, f)$ is the firm's abatement function, which is determined by the reallocation share γ from production and the investment f in abatement technology. Different from the reallocation share of production, which could be treated as a variable abatement cost, the firm's investment in abatement technology is a fixed-cost element. It represents the investment in green capacity, low-carbon patenting, machines, and equipment. The specification of this abatement function is the extension of the ones from Cherniwchan et al. (2017),[5]

$$\Theta(\gamma_i, f_i) = \frac{(1-\gamma_i)^{\frac{1}{\alpha}}}{(f_i)^{\rho}} \tag{1.3}$$

where $0 \leq \gamma < 1$, $f > 0$, $0 < \alpha < 1$ and $\rho > 0$.

From equation (3), the abatement function reflects that firms may reduce emissions through two types of abatement activities: *Reallocation* and *Investment* that incur variable and fixed costs, respectively.[6] Thus, firm can choose either to increase γ or increase f to reduce emission. I follow the standard abatement function form of relocation share, $(1-\gamma)^{\frac{1}{\alpha}}$, from Copeland and Taylor (2004). There is no consensus in previous literature about the functional form of investment in abatement technology because the form is flexible according to each firms' abatement efficiency and engineering design. In order to obtain the estimates of firms' abatement technology level and have the explicit analytical expression for firm's abatement expenditure, here I

[5]In the model of Cherniwchan et al. (2017), their abatement/emission function is a proportional to the use of the dirty input.

[6]I extend the standard formulation of the abatement function in the literature on trade and emissions.

assume the specific functional form of f is f^ρ to facilitate estimation. This specification also implies that firms will invest at least some positive value in abatement as is consistent with the data pattern.

Both α and ρ are abatement technology parameters. $1/\alpha$ captures the reallocating share of inputs elasticity of emission. α is defined as the *reallocating elasticity* and captures the effectiveness of the reallocation technology: a smaller α indicates greater efficiency as $\frac{\partial \Theta}{\partial \alpha} > 0$. With a small α value, firms are more likely to reallocate shares from production to abatement due to more environmental gains through technology efficiency. In other words, with the higher reallocating efficiency, firms generate greater emission reductions by sacrificing the same amount of industrial output. ρ measures the green technology investment elasticity of emission and is defined as the *green elasticity*. It facilitates the effect of green technology investment: a larger ρ indicates greater efficiency as $\frac{\partial \Theta}{\partial \rho} < 0$. Thus, a given measure of investment in green technology would result in more emission abatement with a larger ρ.

I model firms' abatement activities by considering both the variable and fixed-cost elements in a way that closely mirrors the firm's actual abatement technology. As I am going to show, identifying the abatement channels is essential for evaluating the policy effectiveness. In order to achieve the emission reduction target more efficiently, the policy makers should design the policy in line with the firms' current technology status and consider the potential for future green technology innovation.

By combining equations (1), (2), and (3), I obtain an expression of industrial output q as a function of fixed investment, emission and primary factor of inputs as follows:

$$q_i = A_i^{1-\alpha}(f_i)^{\rho\alpha} e_i^{\alpha} (L_i^{1-\mu} K_i^{\mu})^{(1-\alpha)}. \tag{1.4}$$

In equation (4), the production function depends on productivity, investment in green technology, emission, labor, and capital. Note that emission can also be equivalently treated as an input.[7] Given labor and capital, choosing the relocation

[7]This is consistent with Copeland and Taylor (2004).

share γ is equivalent to choosing the emission level e. With such an interpretation, production implies the use of labor, capital, and emissions. The model is based on an underlying assumption of an imperfect substitutability between primary factor of production (labor and capital) and emissions. The parameter α also denotes how intensive the industry is in the use of labor and capital versus the use of emissions. A "dirty" industry will thus be characterized by a high α.

Cost Structure

For each firm i, the Total Cost Function is as follows:

$$C_i = wL_i + rK_i + D_i + f_i + F \tag{1.5}$$

w and r are factor rates, respectively. D is the compliance cost of EU ETS, which I specify below. The compliance cost captures all the costs from the policy, including the emission penalty, costs of purchasing emission credits, and free allowance savings. f_i is the fixed investment in abatement. F is other types of fixed costs, such as the EU ETS administration cost and other fixed investment besides abatement.

Compliance Cost In addition to their usual production cost, firms participating in the EU ETS have to pay for their emissions to comply with the environmental regulations. I construct the policy compliance cost by considering the sales of emission permits. Firms who have enough allowances to cover their emission always have the incentives to sell the spare permits to generate revenue. As a result, some firms participating in the EU ETS could have negative compliance cost through selling their permits allocated by the EU ETS commission.

Each firm is allocated an emission cap $\bar{e}_i$ which is the upper bound of a firm's total emission allowances, and some free emission allowances $\underline{e}_i$. D_i, the compliance cost taking the form of either emission penalty or trading (buying, selling) emission permits according to their emissions, can be written as:

$$D_i(e_i, \tau, \bar{\tau}) = 1_{\underline{e}_i}\tau(e_i - \underline{e}_i) + 1_{\bar{e}_i}(\bar{\tau} - \tau)(e_i - \bar{e}_i) \tag{1.6}$$

where

$$1_{\underline{e}_i} = \begin{cases} -1 & e_i \leq \underline{e}_i \\ 1 & e_i > \underline{e}_i \end{cases} \qquad 1_{\bar{e}_i} = \begin{cases} 0 & e_i \leq \bar{e}_i \\ 1 & e_i > \bar{e}_i \end{cases}$$

When a firm's verified emission exceeds the cap it was given, then the emission penalty for the exceeding part would be:

$$\bar{\tau} = \begin{cases} \text{€40 per } tCO_2 \text{ in phase I} \\ \text{€100 per } tCO_2 \text{ in phase II} \\ \text{€100 per } tCO_2 \text{ with adjustment for the EU inflation rate in phase III.} \end{cases}$$

The relevant member state authority will be responsible for imposing this fine. τ is the observable carbon trading price.

Equation (6) indicates that if the emission of a firm is less than its free allocated allowances, that is $e_i \leq \underline{e}_i$, it pays a negative value for its emission. In another words, it can generate revenue of $\tau(e_i - \underline{e}_i)$ by selling its spare allowances at the market price τ per EUA. If the emission of a firm is greater than its free allocated allowance but less than the cap, that is $\underline{e}_i \leq e_i < \bar{e}_i$, it can purchase emission allowances from primary or secondary market of amount $(e_i - \underline{e}_i)$ at a price of τ per EUA.[8] If $e_i > \bar{e}_i$ or $\Delta e_i < (e_i - \underline{e}_i)$, which means the firm's total allowances (free and acquired) is shorter than the actual emission e_i, then the firm will pay $\bar{\tau}$ per tCO_2 emission as the penalty for failing to compliant. As $\bar{\tau} > \tau$, firms will always be better off purchasing enough allowance to meet the actual emission when $\underline{e}_i \leq e_i < \bar{e}_i$.

[8] Primary market is European Commission and Secondary market is among regulated firms. One EUA is allowed for one ton of CO_2 emission.

Measurement of Policy Stringency

In reality, climate policy may take several forms and does not necessarily set a direct carbon price. Some elements of policy risk are missed out on as a result of the simplification that climate policies will impose costs on investors. Researchers make the convenient modelling assumption that these can be represented in total as an equivalent carbon price. For instance, there may be uncertainty of policy stringency only considering the price of carbon in an emissions trading scheme. Firms face different policy stringency based on their emission level and allocated allowances: the policy is less stringent for firms whose free allowances always cover their emissions; the policy is tighter for firms who purchase EUAs, but without penalties, they care more about EUA prices; the policy is the most stringent for firms who emit over the cap and could not get enough EUAs to cover their emissions, and they care more about penalty fine. Given this fact, it would be biased to only measure policy stringency by the carbon price.

Marginal Cost of Emission I construct the firm-specific policy stringency by using marginal compliance cost of emission:

$$T_i = \frac{\partial D_i}{\partial e_i} = 1_{\underline{e}_i}\tau + 1_{\bar{e}_i}(\bar{\tau} - \tau) \tag{1.7}$$

where

$$1_{\underline{e}_i} = \begin{cases} -1 & e_i \leq \underline{e}_i \\ 1 & e_i > \underline{e}_i \end{cases} \qquad 1_{\bar{e}_i} = \begin{cases} 0 & e_i \leq \bar{e}_i \\ 1 & e_i > \bar{e}_i \end{cases}$$

The equation (7) can be demonstrated in Figure 1.6. As shown in Figure 1.6, it is a step function, and the levels of $\bar{\tau}$ and τ demonstrate the stringency of the EU ETS regime. Firms' emission level and allocated allowances categorize them in different stringency/prices[9]: $-\tau$, 0, τ or $\bar{\tau}$.

[9]See the plots of policy stringency variations among firms and over phases in Figure 1.7.

1.4.2 Model Derivation and Prediction

Model Setup

Demand In the tradition with Dixit and Stiglitz (1977), I assume that there is large, group monopolistic competition between each firm. Thus, the demand function with the perceived elasticity of demand, σ, is as follows:

$$x_i = Bp_i^{-\sigma} \tag{1.8}$$

where p_i is the consumer price and B is a demand shifter, and we are holding income and other factors constant.

Pricing Rule Each firm chooses the same profit maximizing markup over marginal costs equal to $\frac{\sigma}{\sigma-1}$, therefore:

$$p_i = \frac{\sigma}{\sigma-1} MC_i \tag{1.9}$$

where $\sigma > 1$.

Model Solutions

A firm with productivity A chooses its primary inputs: labor L and capital K, the reallocation share γ and investment in green technology f to maximize its profit. The firm follows a two-step decision process. First, it makes choice of the investment f, and second, it maximizes profits taking the investment decision as given. To solve this decision making problem, I adopt backwards induction. After solving this firm's problem, the analytical solutions of fixed abatement investment, emission intensity and reallocation share are presented as follows.

Fixed Abatement Investment As stated in equation (10), a firm's optimal abatement investment depends on productivity, policy stringency, and factor rates.

$$f_i^* = C^{\frac{1}{\nu}} Z^{\frac{1-\sigma}{\nu}} A_i^{\frac{(1-\alpha)(\sigma-1)}{\nu}} T_i^{-\frac{\alpha(\sigma-1)}{\nu}} w^{\frac{(1-\mu)(1-\alpha)(1-\sigma)}{\nu}} r^{\frac{\mu(1-\alpha)(1-\sigma)}{\nu}} \tag{1.10}$$

where $\nu \equiv 1 - \alpha\rho(\sigma - 1) > 0$, $C \equiv (1 - \nu)B(\sigma - 1)^{\sigma-1}\sigma^{-\sigma}$
and $Z \equiv (1 - \mu)^{(1-\mu)(\alpha-1)}\mu^{\mu(\alpha-1)}(1 - \alpha)^{\alpha-1}\alpha^{-\alpha}$.

Emission Intensity Firms choose their inputs of labor, capital, and how much to emit given the fixed abatement investment. I focus on emissions since it is the primary interest. After solving the firm's problem, the emission intensity can be calculated as follows:

$$\frac{e_i}{q_i}^* = C^{\frac{-\alpha\rho}{\nu}} Z^{\frac{1}{\nu}} A_i^{\frac{\alpha-1}{\nu}} T_i^{\frac{\alpha-\nu}{\nu}} w^{\frac{(1-\mu)(1-\alpha)}{\nu}} r^{\frac{\mu(1-\alpha)}{\nu}} \tag{1.11}$$

where $\nu \equiv 1 - \alpha\rho(\sigma - 1) > 0$, $C \equiv (1 - \nu)B(\sigma - 1)^{\sigma-1}\sigma^{-\sigma}$
and $Z \equiv (1 - \mu)^{(1-\mu)(\alpha-1)}\mu^{\mu(\alpha-1)}(1 - \alpha)^{\alpha-1}\alpha^{-\alpha}$.

Equation (11) indicates that a firm's emission choice is conditional on the level of production that is determined by productivity, policy stringency, and factor rates.

Reallocation of Primary Inputs Each firm implicitly decides on the emission intensity and the reallocation share they will divert away from production. The optimal reallocation share incurs the variable expenditure on abatement as follows:

$$\begin{aligned} \gamma_i^* &= 1 - (\frac{e_i}{q_i})^{\frac{\alpha}{1-\alpha}} f_i^{\frac{\alpha\rho}{1-\alpha}} \\ &= 1 - C^{\frac{\alpha\rho}{\nu}} Z^{\frac{\alpha+\nu-1}{(1-\alpha)\nu}} A_i^{\frac{1-\alpha-\nu}{\nu}} T_i^{-\frac{\alpha}{\nu}} w^{\alpha(1-\mu)} r^{\alpha\mu} \end{aligned} \tag{1.12}$$

where $\nu \equiv 1 - \alpha\rho(\sigma - 1) > 0$, $C \equiv (1 - \nu)B(\sigma - 1)^{\sigma-1}\sigma^{-\sigma}$
and $Z \equiv (1 - \mu)^{(1-\mu)(\alpha-1)}\mu^{\mu(\alpha-1)}(1 - \alpha)^{\alpha-1}\alpha^{-\alpha}$.

According to equation (12), the reallocation share of primary inputs is influenced by productivity, policy stringency, and factor rates.

Model solutions reveal that firms' endogenous abatement activities and environmental performance are all related to their productivities and policy stringencies.

Model Propositions

In this subsection, the model predictions derived from equations (10), (11), and (12) are presented, which are consistent with the evidences in Section 3. The following propositions are mainly based on the solutions of equations (10) and (12). They predict that more productive firms are cleaner and mainly driven by larger effort on the *Investment*. However, the more stringent policy rises the *Reallocation* but discourages the *Investment*. The subsequent discussions demonstrate the effects of TFP and policy on abatement activities and emission intensity accordingly.

Effects of TFP

The first theoretical proposition highlights the well-established fact presented in the data. The firms with greater productivity invest more on abatement measured in the fixed tangible assets.

PROPOSITION 1: *Investment increases in firm's productivity, conditional on policy stringency.*

Derived from equation (10):

$$\frac{\partial f_i}{\partial A_i} > 0.$$

This prediction implies that efficient firms will be among the most keen to seize worthwhile resources for cost minimizing or emission reduction opportunities when they arise. Clearly, this is likely to be associated with higher levels of some particular types of abatement investment, such as process-based capital expenditure, and green patenting expenditure. Hence, the productive efficiency enhances the fixed abatement investment.

I now compare proposition 1 with the literature. Cao et al. (2016) state that there is an inverted U-shape investment in abatement technology against productivity, which is supported by Chinese data from a survey. The inverted U-shape investment property is obtained under linear demand derived from the quasi-linear preference under some sufficient conditions. In contrast, my study is based on CES preference, which is consistent with most studies in the literature (Yokoo, 2009; Konishi and Tarui, 2015; Forslid et al., 2018). The different assumption of preference is due to different data patterns between European countries and China. Therefore, they are not inconsistent as they use data from different countries.

The other proposed abatement activity *Reallocation*, together with this *Investment* activity, constitutes a central and novel feature of the model. It is instructive to analyze how these two different abatement activities correlate to each other in terms of productivity effects.

There is a substitution between the two types of abatement activities. A higher *Investment* results in a lower *Reallocation*. It is reasonable to posit that, if a firm decides to allocate a larger fraction of its inputs to emission abatement, then emissions will be reduced. As such, a larger investment to improve the abatement technology is not desirable. Similarly, if a firm has made a large investment on abatement technology, it will need to worry less about the total emission generated from its production; therefore, leaving more inputs for production is optimal.

Consider the characteristics of the two types of abatement activities. *Investment* in green technology not only reduces emissions but also increases output simultaneously. Note that *Investment* releases inputs from the use for abatement, which can then be allocated to production, which in turn raises output. This efficiency-enhancing effect can be seen more directly from equation (4), which clearly indicates that investment in green technology, f, directly enters into the production function. However, *Reallocation* sacrifices production for abatement. As a result, the firm's environmental performance measured by emission intensity, which is defined as emission divided by output, is easier to decrease through *Investment* than *Reallocation*. According to proposition 1, more productive firms put more effort on *Investment* and they lower their effort on *Reallocation* due to the substitution. As a consequence, they also have lower emission intensity than less productive firms. Proposition 2 proves that fact mathematically from the model.

PROPOSITION 2: *More productive firms are cleaner (lower emission intensity).*
Derived from equation (11):

$$\frac{\partial e_i/q_i}{\partial A_i} < 0.$$

As discussed above, more productive firms have a lower emission intensity due to a larger investment in abatement. And the *Investment* has a dominant effect on firm's emission intensity.

Effects of Policy

In addition to productivity effects, I examine firms' abatement responses and environmental performance to changes in the policy stringency:

$$\frac{e_i}{q_i} = (1-\gamma_i)^{\frac{1}{\alpha}-1} f_i^{-\rho}. \tag{1.13}$$

As stated in equation (13), the emission intensity depends on the proposed two abatement activities: *Reallocation* and *Investment.* A given reduction of emission intensity may be reached through either increased reallocated share γ or increased fixed investment f. To respond to an increased policy stringency on emission intensity, a firm can do two things. On the one hand, the firm can reallocate more input from production to emission reduction. On the other hand, it can increase investment in abatement technology to reduce the existing level of pollution. However, at the same time we should also consider the substitution between the two abatement activities. The next two propositions display the policy effects on *Investment* and *Reallocation*, respectively.

PROPOSITION 3: *The abatement investment* ***decreases*** *when policy stringency increases.*
Derived from equation (10):

$$\frac{\partial f_i}{\partial T_i} = -\frac{\alpha(\sigma-1)}{\nu} C^{\frac{1}{\nu}} Z^{\frac{1-\sigma}{\nu}} A_i^{-\frac{(\alpha-1)(\sigma-1)}{\nu}} T_i^{-\frac{\alpha(\sigma-1)}{\nu}} w^{\frac{(1-\mu)(1-\alpha)(1-\sigma)}{\nu}-1} r^{\frac{\mu(1-\alpha)(1-\sigma)}{\nu}} < 0.$$

In line with equation (10), the optimal abatement investments are determined by primary input (labor and capital) rates and the policy stringency. Note that the emission is equivalently treated as an input for production in the model set up. Consequently, we can conclude that the optimal abatement investments depend on input rates: wage, rental rate, and marginal cost of emission, respectively. If the wage or rental rate increases, then the production drops due to the decrease of labor or capital, thus leading to emission reduction. Since the overall emission reduces through output sacrifice, firms would like to put less effort on reducing emission by abatement investment. The same logic holds for the negative policy stringency effect on abatement investment. If the marginal cost of emission increases, then the production drops as the result of emission input decrease, and this lower production leads to overall emission reduction as emission is also a byproduct. This scale effect reduces firms' incentive to invest in abatement technology.

This prediction also reveals the fact that it is hard for firms to adopt better abatement technologies because there are no other cleaner technologies available or because the cost is too high. The higher the current abatement technology level, the lower the investment efficiency due to the decreasing marginal returns on emission. More stringent policy requires more reduction on emissions. Since *Investment* is not a sufficient way, more effort will be put on *Reallocation* due to higher efficiency. *Reallocation* causes production reduction; therefore, less *Investment* is driven by the scale effect.

There is a substitution between the fixed abatement investment f and the variable abatement cost γ. As I demonstrate above, the increase of policy stringency leads to less fixed abatement investment f, as well as production reduction. To be specific, production reduction represents diverting fraction γ of primary inputs and reallocating to emission abatement simultaneously. Proposition 4 below shows the positive policy stringency effect on reallocation share.

PROPOSITION 4: *The reallocation share* ***increases*** *when the policy stringency increases.*

Derived from equation (12):

$$\frac{\partial \gamma_i}{\partial T_i} = \frac{\alpha}{\nu} C^{\frac{\alpha\rho}{\nu}} Z^{\frac{\alpha+\nu-1}{(1-\alpha)\nu}} A_i^{\frac{1-\alpha-\nu}{\nu}} T_i^{-\frac{\alpha}{\nu}-1} w^{\alpha(1-\mu)} r^{\alpha\mu} > 0.$$

Propositions 3 and 4 indicate that policy affects *Reallocation* and *Investment* in opposite ways. Specifically, more stringent policy encourages variable abatement investment from reallocating production share, but decreases the fixed investment in abatement. Therefore, the policy effect on emission intensity is confounding due to the opposite direction of abatement activities. And the overall policy effect on emission intensity depends on which abatement effect is dominant, which is related to the firms' abatement technologies. To put it simply, whether the policy leads to cleaner production or not relies on the magnitude and correlation of the reallocating efficiency parameter α and green efficiency parameter ρ.

PROPOSITION 5: *There is an ambiguous net effect of policy stringency on emission intensity determined by reallocating and green efficiency parameters.*

Derived from equation (11):

$$\frac{\partial e_i/q_i}{\partial T_i} = \frac{\alpha-\nu}{\nu} C^{\frac{-\alpha\rho}{\nu}} Z^{\frac{1}{\nu}} A_i^{\frac{\alpha-1}{\nu}} T_i^{\frac{\alpha-\nu}{\nu}-1} w^{\frac{(1-\mu)(1-\alpha)}{\nu}} r^{\frac{\mu(1-\alpha)}{\nu}}$$

where $\nu \equiv 1 - \alpha\rho(\sigma - 1) > 0$.

The ambiguous net effect of policy stringency on emission intensity highlights the importance of polluters' responses to climate policy and the current abatement technology. The current abatement technology in different types of abatement activities is essential when taking account of policy effect on cleaner production. The policy is more effective in terms of emission abatement in some industries that their reallocating efficiency is high, or green efficiency is relatively low.

The situation when more stringent policy results in higher emission intensity:

If $\rho(\sigma-1) < \frac{1}{\alpha} < \rho(\sigma-1)+1$, then,

$$\frac{\partial e_i/q_i}{\partial T_i} > 0.$$

The situation when more stringent policy results in lower emission intensity:

If $\frac{1}{\alpha} > \rho(\sigma - 1) + 1$, then,

$$\frac{\partial e_i/q_i}{\partial T_i} < 0.$$

Given the fixed markup, if the inverse reallocating efficiency parameter $\frac{1}{\alpha}$ is large enough or the green efficiency parameter ρ is small enough, then γ_i effect is more dominant than the f_i effect under the policy shock. Therefore, the overall policy effect on emission intensity is γ_i driven, which is negative.

Then the paper tests for the effectiveness of the EU ETS in selected carbon-intensive manufacturing sectors.[10] The estimates are consistent with the more stringent policy results in cleaner production from encouraging variable abatement activity in the short run rather than from fixed abatement investment in the long run. The estimated abatement technology parameters shed light on the current abatement technology in some carbon-intensive manufacturing sectors: their reallocating efficiency is much higher than the green efficiency. The results are consistent in that these sectors have higher carbon leakage risk than other regulated sectors, such as power and energy sectors.[11]

PROPOSITION 6: *More productive firms are more responsive to policy changes if reallocating efficiency (green efficiency) is high (low); Less productive firms are more responsive to policy changes if reallocating efficiency (green efficiency) is low (high).*
The following situation accounts for how more productive firms are more responsive to the policy stringency:

If $\frac{1}{\alpha} > \rho(\sigma - 1) + 1$, then,

$$\frac{\partial^2 e_i/q_i}{\partial T_i \partial A_i} > 0.$$

[10]Petroleum and Coke; Metals including iron and steel; Chemicals; Pulp and Paper and Non-metallic minerals.

[11]*Carbon leakage* is a term to describe the situation that, for reasons of costs related to climate policies, firms reallocate production to other countries with less or without the regulation.

When reallocating efficiency is high, the γ_i effect is more dominant than f_i effect. More stringent policy leads to cleaner production. More productive firms have a larger scale of production; therefore, they have greater resources directed towards abatement and thus greater γ_i. Therefore, in this case, more productive firms are more responsive to the policy stringency.

The situation when less productive firms are more responsive to the policy stringency:

If $\rho(\sigma - 1) < \frac{1}{\alpha} < \rho(\sigma - 1) + 1$, then,

$$\frac{\partial^2 e_i/q_i}{\partial T_i \partial A_i} < 0.$$

When green efficiency is high, the f_i effect is more dominant than γ_i effect. More stringent policy leads to dirtier production, that is, larger emission intensity. The abatement is diminishing while the policy stringency increases because it becomes harder and harder for firms to respond when approaching to more and more efficient green technology. Since more productive firms are adopting greener technology from more fixed investment, they have lower abatement driven by f_i effect. Therefore, in this case, less productive firms are more responsive to the policy stringency.

1.5 Empirical Design

Putting the analysis into motion requires data of emission intensity, investment in green technology, and policy stringency, as well as estimates of productivity and markup. The biggest challenge is reliable data of firms' abatement investment which cannot be observed; therefore, I focus on emission intensity, equation (11), which can be observed directly. The policy stringency can be constructed by data. In the theory part, I have allowed for firm heterogeneity in production and assumed CES demand. I thus borrow the method of TFP estimation developed in Ackerberg et al. (2015) (ACF), which yields consistent estimates of TFP. For markup estimation, I have adopted two methods following Hall et al. (1986) and De Loecker and Warzynski (2012). The extended discussion is as follows.

1.5.1 Policy Stringency from Data

I observe firms' verified emissions, free allowances, and total emission credits surrendered each year during regulation periods. If a firm's surrendered emission credits are less than free allocated allowances, then the firm sells credits thus pays negative compliance cost. If a firm's surrendered emission credits are greater than free allocated allowances, then it indicates that the firm purchases credits from primary or secondary market. Moreover, if a firm's surrendered emission credits are less than verified emissions, then the firm has to pay for the penalty. And if a firm's surrendered emission credits are the same as verified emissions, then the firm does not pay for the penalty. There is no incentive for firms to submit more credits than their emissions, even though they have credit surplus. It is always better off for firms to choose either reserve the credits for future periods or sell them to other firms who are short of credits at the current stage. By calculating firms' policy stringency according to equation (7), firm's policy stringency distribution by phase is demonstrated in Figure 1.7.

Some facts could read from the distributions. First, there is a sizable portion of firms that have spare emission credits. They actually could generate revenue through selling their unused permits; thus, they face negative marginal compliance cost. Second, the number of firms that have surplus emission permits is decreasing over phases. Third, the average policy stringency becomes tighter and is mostly driven by increased portion of firms paying for penalty and decreased allocated allowance. The constructed policy stringency indicator includes both positive and negative values. For calculation reason, I first normalize the policy stringency (marginal compliance cost) within the range of 0 to 1, then apply the log transformation for regressions.

1.5.2 Estimation

Estimation of Productivity

Firm productivity is measured by total factor productivity (TFP). I follow Ackerberg et al. (2015) (ACF) to use the variation in intermediate input, materials, to proxy the unobservable productivity shocks, thus reducing the simultaneity problem. The production function is estimated by sector following ACF method. The output elasticities are reported in Table 1.3. The sum of the coefficients for each sector is also reported. Most sectors imply increasing returns to scale, though we cannot reject the null that the sum is one at the 5% significant level. My estimates are consistent with ones in the literature.[12]

The estimated input coefficients and TFP statistics of all manufacturing sectors are given in Table 1.4. For robustness check, I also compare parameter estimates with ones in the LP approach by Levinsohn and Petrin (2003) and in the DLW approach by De Loecker and Warzynski (2012). In addition, two estimation cases are checked robustly. Panel (1) presents the estimation when the dependent variable is gross revenue and proxy variable is material. Then I turn to using value added as the dependent variable and emission as the proxy variable, and the results are reported in panel (2). The DLW estimation results of labor and capital elasticities of output are based on the trans-log production function. In contrast to the Cobb–Douglas production function in ACF method, the trans-log production function makes a variation in these elasticities and gives an estimation of mean productivity with 2.91.[13] The estimated TFP distributions by three approaches are presented in Figure 1.9. Overall, the output elasticities of three estimation approaches and two estimation

[12]De Loecker et al. (2016) estimate output elasticities by sector using Indian firms data; they report the material shares are in the range of 0.6-0.8, and capital shares are in the range of 0.01-0.2. Dobbelaere and Mairesse (2013) report the input shares of labor, material, and capital are 0.307, 0.503, and 0.190, respectively using panel data in French firms.

[13]De Loecker and Warzynski (2012) propose the estimation procedure by extending the TFP estimation approach developed by Ackerberg et al. (2015). Unlike the Cobb–Douglas production function, De Loecker and Warzynski (2012) consider the trans-log production function to capture firm heterogeneity.

cases are consistent with ones in the literature. My main results in this study are based on Ackerberg et al. (2015) (ACF) of TFP estimation.

Estimation of Firm's Markup

Table 1.5 reports the median markups estimated by using two methods. Method 1 relies on the firm's optimal condition of cost minimization with respect to a static input. By following the insights from Hall et al. (1986) and De Loecker and Warzynski (2012), I use material inputs for markup estimations because materials do not suffer much from adjustment costs or other dynamic considerations. The firm-level markup is proportional to the inverse of the material cost share of revenue. For calculation, the markup equals to the output elasticity of material times the inverse of the material cost share of revenue (Cassiman and Vanormelingen, 2013). The median markups are in the range of 1.12-1.58 as reported.

Method 2 is based on accounting markup, which is widely introduced in the empirical industrial organization literature. It is often used as an imperfect measure for market power. When firms have constant returns to scale and totally fixed capital costs, the accounting markups are suppose to equal to the precise markups. Here I take advantage of the observed profit margin and cost of goods sold information in the data and compute the accounting markups. Then, I compare them with the estimate for the true markups. The firm-level markup is calculated by $\frac{1}{1-ProfitMargin}$.[14] The median accounting markups are in the range of 1.09-1.31. The estimated markups using both methods are in line with the literature.[15] Generally, firms' estimated markups are greater than the accounting markups as we expected. Theoretically, the average variable costs overestimate the marginal costs under increasing returns

[14]The accounting markups are also checked robustly by sales divided by costs of goods sold.

[15]For example, Siotis (2003) found an average price-cost margin of around 0.25 (which implies a markup of 1.33) for Spanish manufacturing firms in the beginning of the 90's. Abraham et al. (2009) reported an average markup of 1.29 in their sample of Belgian manufacturing firms. De Loecker and Warzynski (2012) reported the median markup to be in the range of 1.17-1.28 for Slovenian manufacturing firms. De Loecker et al. (2016) estimated the median markup to be in the range of 1.15-2.27 for Indian manufacturing firms.

to scale so that the accounting markup underestimates the true markup. As stated in Table 4, firms in most covered sectors experience increasing returns to scale. The reason that the estimated markup is less than the accounting markup, such as results in chemical sector, could be because the part of the capital costs are variable costs. Therefore, the accounting markup could overestimate the true markup especially for firms with high capital intensity.

Regression Equation

Taking the natural logs of equation (11) results in the following linear specification:

$$ln(\frac{e_i}{q_i}) = Constant + \frac{\alpha - 1}{\nu} ln(A_i) + \frac{\alpha - \nu}{\nu} ln(T_i) \tag{1.14}$$

where

$$Constant \equiv \frac{-\alpha\rho}{\nu} ln(C) + \frac{1}{\nu} ln(Z) + \frac{(1-\mu)(1-\alpha)}{\nu} ln(w) + \frac{\mu(1-\alpha)}{\nu} ln(r).$$

Equation (14) indicates the regression equation as follow. For any manufacturing firm i in region j in year t:

$$ln(\frac{e_{ijt}}{q_{ijt}}) = \beta_0 + \beta_1 ln(TFP_{ijt}) + \beta_2 ln(T_{ijt}) + \eta_r + \eta_d + \eta_y + \eta_f + \eta_{rdy} + \epsilon_{ijt}. \tag{1.15}$$

Emission intensity is calculated by the verified emission divided by revenue.[16] Firm productivity is measured by total factor productivity (TFP) using the method of Ackerberg et al. (2015) (ACF), as I discussed above. Policy stringency (T) is constructed by free allowance, verified emissions, EUA price, and penalty cost of each firm, as stated in Section 5. Wage and rental rate are treated as constant and absorbed by firm-fixed effects.

To control for unobservable location, industry, time, and firm characteristics, I include several fixed effects in the regression. The η_r and η_d control for the variations of region and sector activities. The year fixed effect, η_y, picks up time trend and

[16] I also calculate the emission intensity as emission divided by value added and emission divided by sales, the data quality is better by using emission divided by revenue.

phase variations in emissions. These variations include but are not limited to policy administration and governor changes over phases. For example, phase I works as a pilot "learning-by-doing" period preparing for the following phases. It allows firms to use international offset certificate staring from phase II. The cap of the EU ETS becomes a single EU cap from national caps at the beginning of phase III. The aforementioned changes across phases all have potential influences on emissions other than my main interest. The firm-fixed effect, η_f, controls for other unobservable characteristics within firms, such as the diversification of installations the firm owned; either the firm is government-owned or family-owned. I also include region by sector by year fixed effects, η_{rdy}, to control for demand shocks, the constant C part in the model.

Endogeneity Issue and IV

There is a loop of causality between policy stringency and emissions. Policy regulates firms' production and emission behaviors, and in turn, emission levels also influence the determination of policy stringency. In this case, the policy stringency is not exogenous. To solve this simultaneity endogeneity issue, I adopt instrument variables to instrument policy stringency. This study builds on literature in environmental economics, trade, and environment. Existing studies commonly documented that measuring regulatory stringency involves a particular feature of many environmental regulations: they are "grandfathered" or "vintage-differentiated", meaning they are stricter for new sources of pollution than existing sources (Brunel and Levinson, 2016). Therefore, I use capital vintage of the firm as the instrument variable for policy stringency. The capital vintage is measured by firms' capital depreciation, which could be directly observed from the data. The identifying assumption is that the changes in a firm's yearly capital depreciation are unrelated to changes in the firm's annual emission intensity, except through the policy stringency after flexibly controlling for a large number of fixed effects. The capital depreciation is negatively correlated with policy stringency because regulatory standards are typically stricter for new sources of pollution, which may result in firms keeping older plants in operation longer, thus affecting measures of regulatory stringency. The variations of log value of capital depreciation and policy stringency are shown in Figure 1.8.

1.6 Results

1.6.1 Main Results

Emission Intensity

Table 1.6 reports the estimates of equation (15) with the OLS, Two-Stage Least Squares (2SLS), and First Difference (FD) methods. Moving through the columns of Table 1.6, the different specifications of fixed effects are imposed. Consistent with the data pattern and model prediction, the firm's productivity plays an important role on emission intensity. Thus, the coefficients for productivity are negatively significant with 1% increase in productivity leads to 0.1%-0.3% drop in emission intensity. Put another way, more productive firms are cleaner with lower emission intensity. The estimated TFP effect is consistent with Forslid et al. (2018), which report that there is a 0.16%-0.42% drop in emission intensity as a result of 1% increase in TFP.

The theory of this paper predicts that the impact of policy stringency on emission intensity is undetermined; thus, the influence of policy on firm's emission intensity is an empirical question. The estimation results show that the coefficients for the policy stringency are negatively small but statistically significant at the 1% level in all specifications. It implies that there is a negative significant effect of policy stringency in terms of allowance and carbon prices on emission intensity. Specifically, a 1% increase in policy stringency results in around 0.1% reduction in emission intensity. As established in Section 4, where we discussed the construction of policy stringency, policy stringency is defined as the marginal compliance cost of EUA permit conditional on a firm's free allowance position. To be specific, firms that are short on free allowance, denoted as *Short*, will face a policy stringency as EUA permit market price. Firms that are in excess of their free allowance, denoted by *Long*, will have a negative cost of compliance and will pay a negative EUA permit market price through selling permits. Firms that did not surrender their emissions, noted as *Penalty*, will suffer a penalty price per unit as a policy stringency. The economic interpretation of a 1% increase in policy stringency varies depending on the firm's free allowance position in above categories. It is a 1% increase in EUA permit market price for *Short* firms, a 1% decrease in EUA permit market price for *Long* firms, or a 1% increase in penal sum for *Penalty* firms.

To the best of my knowledge, there are no other studies that have estimated the emission intensity elasticity within the EU ETS stringency. The existing studies have been largely focused on estimating the emission reduction during the EU ETS regulation phases, but there is little known about the change of emission intensity (Wagner et al., 2014a; Wagner and Petrick, 2014; Dechezleprêtre et al., 2018). My study contributes to this on-going debate of whether the EU ETS impacts the emission intensity. The emission intensity elasticity is not only to estimate the emission reduction during past phases but also to speak to the policy efficiency on the trade-offs between emission abatement and industrial production. Overall, obtaining the emission intensity elasticity of the EU ETS is important for better evaluating the policy in past phases and further directing the scheme in future design.

Abatement Technology Parameters

After obtaining the above coefficients (β_i) from the regression directly, I am able to estimate two abatement technology parameters: the reallocating (α) and green elasticities (ρ). Both α and ρ capture the effectiveness of the standard abatement technology: a larger α indicates lower inputs efficiency while a larger ρ presents higher investment efficiency.

α represents the elasticity of allocating the inputs, more specifically, the trade-off between production and emission abatement. According to the production and emission equations, the resource or input used to produce 1 unit of industrial output could be reallocated to reduce $\frac{1}{\alpha}$ unit of emissions. This follows Copeland and Taylor (2004), their specification of resource allocation. Specifically, given any emission abatement technology to a firm, by devoting some inputs to abatement, the firm can reduce its emission level. α measures this trade-off effectiveness and indicates how elastic the reallocation is. ρ captures the elasticity of low-carbon technology investment, specifically the investment on improving the quality of capital (machine and equipment). Assume the better quality of the capital and the technology, the lower emissions without hampering outputs.

According to the empirical design, the coefficient β_1 indicates the effect of TFP on emission intensity, and β_2 measures the impact of policy on emission intensity. After calculation and substitution, we can obtain the two elasiticities.

The reallocating elasticity:

$$\frac{1}{\alpha} = \frac{1 + \beta_2 - \beta_1}{1 + \beta_2} \tag{1.16}$$

The green elasticity:

$$\rho = \frac{\beta_2 - \beta_1}{1 + \beta_2} \frac{1}{\sigma - 1} \tag{1.17}$$

According to equations (16) and (17), both elasticities depend on the effect of TFP and policy on emission intensity. Note that ρ is highly sensitive to the markup effect. Holding the effects of TFP (β_1) and policy (β_2) fixed, if we compare two similar industries with different markups ($\frac{1}{\sigma-1}$), the reallocating elasticity is indifferent while the green elasticity is smaller for the one industry with a higher σ, or a lower markup. I next discuss the values of these two elasticities. Derived from equations (16) and (17):

$\frac{1}{\alpha} > \rho$, if $\sigma > \frac{\beta_2-\beta_1}{1+\beta_2-\beta_1} + 1$, and $\frac{1}{\alpha} < \rho$, if $1 < \sigma < \frac{\beta_2-\beta_1}{1+\beta_2-\beta_1} + 1$, since $\frac{\beta_1}{1+\beta_2} < 1$ and $\sigma > 1$ from the model assumptions in Section 4.

We can rewrite the above relationships more intuitively. The reallocating elasticity is greater than the green elasticity ($\frac{1}{\alpha} > \rho$), conditional on:

$$0 < \underbrace{\frac{1}{\sigma - 1}}_{\text{markup}} < \underbrace{\frac{1}{\beta_2 - \beta_1}}_{\text{inverse of effects difference}} + 1.$$

Here the "inverse of effects difference" represents the inverse of the difference between policy and TFP effects. This condition interprets that the firms may have a higher efficiency on emission reduction to use of inputs than to invest in abatement technology when the markup is less than the inverse effects difference (a relatively smaller markup). The reallocating elasticity is smaller than the green elasticity ($\frac{1}{\alpha} < \rho$), conditional on:

$$\underbrace{\frac{1}{\sigma - 1}}_{\text{markup}} > \underbrace{\frac{1}{\beta_2 - \beta_1}}_{\text{inverse of effects difference}} + 1.$$

Similarly, the firms may have a higher efficiency on emission reduction to invest in abatement technology than to use of inputs when the markup is larger than the inverse of effects difference (a relatively bigger markup).

The estimated parameters are reported in Table 1.7. The reallocating and green elasticity parameters are obtained from the given markup. I take σ as 5.5 according to my estimation, which implies a markup of 1.22. The reallocating elasticity is much higher than the investment elasticity, which indicates that firms have a higher efficiency in their use of inputs than in their use of green technology investment. In addition, the markup is less than the inverse of difference between policy and TFP effects. The revealed parameters may converge with the fact that the current green technology is approaching a level, which makes the emission abatement through technology investment quite limited. Some studies show the similar patterns. For example, Huang et al. (2014) state that Shenzhen ETS in China is a main driver for the technological investment of the regulated industry, but the effect of emission is quite limited in the long-term simulation. The existing literature that only contains *Reallocation* channel, has a small estimation value of their reallocating elasticity (Shapiro and Walker, 2018). Their emission intensity function does not distinguish the fixed abatement investment from the abatement cost share, therefore, the elasticity they estimated should be a combined elasticity parameters of α and ρ in this study. Shapiro and Walker (2018) report the pollution elasticity of mean across industries as 0.011. Consistent with theirs, my combined elasticity values are in the range of 0.002-0.009, which are the pollution elasticities defined in Shapiro and Walker (2018).[17]

The CO_2 emission intensity is explained by input share reallocation γ and low-carbon technology investment f as referred to equation (13). With the estimated parameters, I am able to demonstrate the change of emission intensity due to a 1% increase in *Reallocation* or *Investment* accordingly. Specifically, holding the investment fixed, a 1% decrease in production share leads to a 0.18%-0.21% decrease in CO_2 emission intensity. While a 1% increase in low-carbon technology investment results in 0.01%-0.04% decrease in CO_2 emission intensity keeping reallocation share fixed. This confirms that firms have higher efficiency in use of inputs than in use of low carbon technology investment. The relatively small effect on emission intensity of investment channel is due to the small value of green elasticity. According to my estimation, the policy stringency drives a large effect on green technology investment (f) but a tiny impact on emission intensity, which reveals a small green elasticity (ρ).[18]

1.6.2 Decomposition

To better understand the effectiveness and efficiency of firms' current abatement activities, the decomposition results of the observed CO_2 emission intensity changes over time are obtained in this subsection. In addition, the predicted CO_2 emission changes and their decomposition are also discussed here in order to provide some insights for policy makers.

[17] According to equation (13), the combined emission elasticity is $\frac{(1-\alpha)*\rho}{\alpha}$, which is the pollution elasticity value estimated in Shapiro and Walker (2018).

[18] The numbers are calculated and reported in Table 1.8.

Decomposition Coefficients

I first calculate and report the coefficients of decomposition based on an effect of 1% increase in policy stringency. The total CO_2 emission intensity change is attributed to the effect of input share reallocation and low carbon technology investment, and some relationships are summarized in Table 1.8. First, according to equations (10) and (12), the policy effect on both channels could be obtained in columns (2) and (3) of Table 1.8. By plugging in the value of estimated parameters from Table 1.7, we find that, when the policy stringency increases by 1%, production share after reallocation, $1-\gamma$, decreases by 0.89%-0.98% while low carbon technology investment, f, decreases by 3.99%-4.40% depending on estimation method. Additionally, I compute how policy stringency affects the emission intensity through both channels directly. As demonstrated in columns (4)-(6), the total 0.11% (0.02%) CO_2 emission intensity decrease due to a 1% increase in policy stringency could be decomposed to a 0.16% (0.21%) decrease in CO_2 emission intensity through *Reallocation* and a 0.05% (0.18%) increase in CO_2 emission intensity through *Investment*.

The Actual CO_2 Emission Intensity

The decomposition results of the CO_2 emissions intensity in log value changes across three phases are listed in Table 1.9. The total CO_2 intensity change is attributed to the effect of policy stringency and productivity. In this paper, we focus on the policy effect. The part of CO_2 intensity change explained by policy can be further decomposed into the effect of *Reallocation* and *Investment*. Some findings are as follows.

The first two columns are directly obtained from the data. Column (1) in Table 1.9 records the mean log value of real emission intensity changes over time. According to the data pattern, we observe that the emission intensity decreases across phases in the sample. The amount of decrease is small in both phases I and III, but a relatively larger reduction is observed in phase II with around 0.4% in average. If we look at the emission intensity changes by year, we find that a larger reduction is observed during the period when shifting phases (2005-2006; 2007-2008; 2011-2012).[19] Column (2) in Table 1.9 demonstrates the mean log value of policy stringency changes over time. The policy stringency increases during phase I and phase III, while it decreases during phase II due to the over-allocated free allowance in the recession period. Column (3) in Table 1.9 reports the mean value of real emission intensity change explained by policy stringency. The values are around 0%, which indicates a limited impact of policy stringency on cleaner production. A relatively larger value appears during transfer periods driven by the larger changes of policy stringency. The aggregate policy effect on emission intensity by phases indicates that the policy-driven emission intensity decreases by 0.49% and 0.31% during phase I and phase III, respectively, but increases by 3.83% during phase II.[20] These results provide additional evidence to address the ambiguous findings of emission intensity change due to the EU ETS in the literature. My estimates suggest that there is a small emission intensity decrease even though there were large emission reductions during the EU ETS regulation. Klemetsen et al. (2016) find some evidence that Norwegian-regulated plants reduced emissions by a large amount (-30%) in the second phase of the EU ETS, but there is no evidence that emission intensity decreased in any of the EU ETS phases. Egenhofer et al. (2011) find that, during 2008 to 2009, the EU ETS improved the overall emission intensity by 3.35% on average, while this figure drops to 0.45% for the manufacturing sectors only.

Different from other phases, we notice that in phase II, there is a decrease of 0.37% on average on observed emission intensity while the emission intensity driven by the policy rises. Phase II covers the recession period, during which a large number of old and emission-intensive plants reduced production, and some were even selected out of the market (Bae, 2017). The observed emission intensity decreases mainly due to reduced production of "dirty" plants. At the same time, the policy is too generous

[19] The decomposition of CO_2 emission intensity by year is reported in Appendix of Table B.4.

[20] 98 firms are observed during phase I; 958 firms are observed during phase II and 1003 firms are observed during phase III.

in terms of over-allocation. The decrease in policy stringency slows down firms' effort on emission abatement and green innovation, resulting in emission intensity increase. Overall, the selection effect is more dominant during phase II so that we still observe a drop in emission intensity. Based on the coefficients in Table 1.8, columns (4) and (5) in Table 1.9 present the mean values of policy stringency effect on channels *Reallocation* and *Investment*. For instance, the policy stringency increases by 0.09% on average during 2005-2016, then production share after reallocation, $1-\gamma$, decreases by 0.088% and abatement investment, f, decreases by 0.396%. Therefore, the emission intensity drops as a result of that the *Reallocation* effect dominates the *Investment* effect.

The further decomposition of policy effect on emission intensity into two channels reveals that, consistent with the model predictions, the *Reallocation* and *Investment* are substitutes and have opposite impact of emission intensity. As shown in columns (6) and (7) of Table 1.9, if one channel has positive effect on emission intensity, the other has the negative impact. In order to understand the contribution of each channel on observed emission intensity, I report the channel impact, which shares the same direction of movement with the observed emission intensity change. The results indicate that the channel of *Reallocation* explains 28% and 7% observed emission intensity decrease in phase I and phase III, respectively. Meanwhile, a 9% observed emission intensity drop in phase II is driven by the channel of *Investment*. Overall, during the regulation period from 2005 to 2016, a 3% verified emission intensity decrease is explained by the *Reallocation*. To my best knowledge, the similar decomposition of the EU ETS effect has not been adequately analyzed in other studies. These results, which address the gap in the literature, are the main contributions of the paper.

The Predicted CO_2 Emissions

In Table 1.9, I demonstrate the observed CO_2 emission intensity decomposition into two channels, which helps to better understand the model mechanisms empirically. Next, I move to discuss some results of policy implications. The decomposition of predicted CO_2 emission changes across phases based on model predictions is reported in Table 1.10. Taking phases as intervals can better explain the impacts of policy stringency adjustment on CO_2 emission changes over special transferring periods. The percentage change by phases is also recorded in brackets in Table 1.10. Columns (1), (2), and (9) are directly obtained from the data representing the percentage change in policy stringency, the percentage change in value of production, and the amount change of real emission accordingly. According to the model predictions, equation (14), the emission intensity change is driven by exogenous policy stringency and productivity. Holding the productivity (A) fixed, I am able to calculate the corresponding changes of emission intensity due to policy stringency changes following my estimations. Column (3) in Table 1.10 reports this predicted emission intensity change driven by policy. The decomposition results of predicted emission intensity into *Reallocation* and *Investment* channels are shown in columns (4) and (5) based on coefficients in Table 1.8. In order to directly compare the results with the ones in the literature, I further obtain the emission changes based on the emission intensity changes because I observe firms' output as well. Column (6) is the predicted total amount of emission change obtained based on emission intensity change. The predicted total amount of CO_2 change is attributed to the effect of *Reallocation* and *Investment*, and they are demonstrated in columns (7) and (8). We can obtain some information from Table 1.10 as follows.

First, CO_2 emissions in the regulated manufacturing industry decreased by 68 million tons from 2005 to 2016, which is equivalent to an abatement of 25.68% based on the emissions in year 2005.[21] This indicates that, at least for manufacturing industry, the EU ETS has already achieved the goal of emission reduction for phase III.[22] Specifically, the *Reallocation* effect is the dominating contributor to the decrease of

[21]The CO_2 emission in 2005 is 265.699 million tons according to own calculation based on the matched sample.

[22]The Emissions target before 2020 is a 21% reduction of greenhouse gases compared to the year of 2005. In 2030, under the revised system, they will be 43% lower.

CO_2 emissions, and it accounts for 77 million tons of total CO_2 change. The *Investment* effect explains about only 9 million tons, or 13.3% of the change of CO_2 emissions. Second, my predictions suggest that there is a small emission intensity decrease, even though there are large emission reductions during the EU ETS regulation. The manufacturing firms reduce emissions by 25.68% during 2005 to 2016 while the emission intensity decreases 9.59%. Third, the *Reallocation* effect dominates during all periods of the EU ETS regulation; while we also observe that from 2007 to 2008 and 2012 to 2013, *Investment* had a larger effect in comparison with other time periods. Interestingly, these were two periods when the EU ETS phases were shifting.[23] Abrell et al. (2011) estimate CO_2 emission reductions induced by the transition from phase I to phase II. Controlling for revenue, employment, profit, and industry and country trends, they find that emission reductions were 3.6% higher between 2007 and 2008 than between 2006 and 2007. They argue that the reduction in emissions is due to the change in stringency from phase I to phase II and not to a decrease in production. My result of predicted emission intensity change confirms this pattern and further explains that a stronger *Investment* effect during the transition period of phases leads to a change of emission controlling for output, or change in emission intensity. One explanation of this "transition period effect" is that firms are most likely to take effort on abatement when they need to face policy adjustment uncertainties during the transition period, particularly at the end of each phase cycle (Guo et al., 2018).

The verified emissions data in column (9) of Table 1.10 shows that there were a 9.2% increase, 21.1% decrease, and 9.8% increase in actual carbon emissions of all regulated manufacturing installations in phases I, II and III, respectively. The difference between my predicted emission changes caused by the EU ETS and the real emission changes from the data indicates that observing emissions to be changing does not necessarily mean that the EU ETS is the cause of this change. There could have been emission changes also in the absence of the EU ETS, for example, due to

[23] The decomposition of predicted CO_2 emission by year is reported in Appendix of Table B.5.

technological progress or macroeconomic factors such as business cycle fluctuations. My model identifies another factor which is the productivity.

I further compare my estimated causal emission changes due to the EU ETS with the ones in the literature. As shown in Table 1.11, the results cover the scope of literature that looked at the impact on carbon emissions during the first two phases of the EU ETS. My estimates present a 132 million tons CO_2 emission reduction from 2005 to 2006, which is consistent with Ellerman and Buchner (2008), who estimate that CO_2 emissions were reduced by between 100 and 200 million tons across all EU ETS countries for the year from 2005 to 2006. Anderson and Di Maria (2011) demonstrate that the overall emission abatement during the first phase of the EU ETS is 247 million tons using a dynamic panel model. My results predict that the manufacturing sectors' emission abatement during the first phase of the EU ETS is 63 million tons, according to my proposed model in the paper. The estimated emission intensity elasticity indicates a 16.62% of CO_2 emission reduction during phase II of the EU ETS. This corresponds to roughly 44 million tons CO_2 emission. Similar results are found in several studies. Wagner et al. (2014b) show that ETS-regulated manufacturing plants in France reduced emissions by an average of 13% compared to a control group of similar but unregulated installations during phase II, suggesting that the EU ETS was effective at reducing carbon emissions of regulated plants. Dechezleprêtre et al. (2018) report that EU ETS led to a reduction of emissions by 6% to 19% in manufacturing sectors during the first two phases.

1.6.3 Results by Sector

The estimation is performed by different manufacturing sectors as well. Based on European industry standard classification system (NACE), we focus on three general manufacturing sectors, non-metallic minerals, pulp and paper, and basic metals. Two other sectors' results are not reported due to small sample size.[24] As shown in Table

[24]Results of Chemicals, Petroleum and Coke are included in main result not reported by sector.

1.12 and Table 1.13, there are some variations across different sectors. Table 1.12 displays the regression results by sector. All sectors tend to have a negative emission intensity elasticity of policy effect between -0.082 and -0.136. The preferred specification, shown in column IV3 of Table 1.12, suggests that the effect of the EU ETS may have been stronger in basic mental and non-metallic mineral products sectors, and the estimated coefficients are statistically greater than in other sectors. Dechezleprêtre et al. (2018) find that, in comparison with other sectors, the impact of the EU ETS on chemical, non-metallic mineral, and electricity sectors is larger. However, their results only consider four countries, and the coefficients lack statistical significance due to small sample size. My estimates conclude that, there may have been small heterogeneity of the impact across sectors, and all sectors seem to experience a decline in their carbon emission if policy becomes tighter. Different from the policy effect, there seems to be a larger variation in productivity effect on emission intensity across sectors. For instance, the productivity impact on emission intensity is nearly five times larger in the sector of pulp and paper than in non-metallic mineral and basic mental sectors.

As presented in Table 1.13, the results show the variations of technology parameters across sectors. Overall, the reallocating elasticity is higher than the green elasticity. Specifically, the estimated reallocating elasticity and green elasticity parameters are in the range of 0.54-0.88 and 0.01-0.23, respectively. The sector of pulp and paper seems to have relatively larger green elasticity than other regulated manufacturing sectors. This may be due to there being more available technologies of abatement in pulp and paper sector than in more traditionally operated industries such as metals and coke. For example, the development of black liquor gasification technology could improve the safety and efficiency of the chemical-recovery process in paper production and reduce emissions of air pollutants (National Academy of Engineering, 1998).

The decomposition of CO_2 emission intensity by sector is reported in Table 1.14. According to the results, policy has a tiny and limited impact on firms' cleaner production across all three sectors. The emission intensity slightly increased during 2005 to 2016 in each sector since the policy stringency decreased largely due to economy recession. *Reallocation* channel explains more emission intensity changes than *Investment* channel in each sector. Specifically, during 2005 to 2016, *Investment* drives 8% and 21% real emission intensity reduction in the sector of non-metallic mineral and pulp and paper, respectively. In the mean time, *Reallocation* explains 2% real emission intensity rise in basic metal sector. In addition, the decomposition of predicted CO_2 emission by sector is demonstrated in Table 1.15. As what we expect, all three sectors have decreased emissions by policy stringency drop due to over-allocation in phase II. However, the predicted policy-driven emission intensity has increased in phase II as a result of large production decline but small emission abatement effort under loose policy stringency during recession. There may have been heterogeneity of the impact across sectors. The estimation suggests that, from 2005 to 2016, non-metallic mineral firms have increased CO_2 emissions by 44.8 million tons, which is equivalent to 29.7% rise based on emissions in year 2005. Other two sectors: pulp and paper, basic metal, have reduced CO_2 emissions by 56 million tons (86%), and 67 million tons (22%) accordingly since 2005. Among all three sectors' emission change, *Reallocation* dominates and explains the most of the emission changes. Most studies in the literature that aim at analyzing the impact of the EU ETS on emission reductions are forced to make use of simulations rather than ex-post analysis because of the scarcity of disaggregated data and the complexity of the European market. Studies adopted diff-in-diff method to do an ex-post analysis on emission level focus on one country or one specific sector for the same data unavailability issue. Dechezleprêtre et al. (2018) suggest that the effect of the EU ETS has decreased emission level in non-metallic mineral products based on their estimation of four countries. The difference between my results and theirs indicates heterogeneity across countries.

1.7 Conclusion

This paper explores the impact of the EU ETS, Europe's flagship climate change policy, on carbon emissions by developing an emission abatement framework with two channels, *Reallocation* and *Investment*, through which firms are abating. Prior work mostly uses survey data to show the firm-level drivers of emission change. To the best of my knowledge, this is the first study to establish a framework to assess the two channels of emission abatement empirically through the use of compliance data. Moreover, this is the first study to estimate emission intensity elasticity due to the EU ETS, which allows for evaluating the cleaner production and green innovation, thus revealing the long-term objective of the EU ETS.

Although reallocation of inputs or resources across firms has received great attention in economics, less emphasis has been given to in-firm reallocation. In this paper, I have highlighted firms' reallocation of primary factor of production (labor, capital) as a source of firm's emission abatement. This paper could complement those that emphasize resource reallocation and capital accumulation (investment on green technology) as crucial to firms working to negotiate environmental policy shocks. Especially, in the short run, a carbon-intensive facility may choose to reduce outputs in order to keep balance of production cost and policy compliance cost. Furthermore, I shed light on this heterogeneous emission abatement process by showing how the two proposed channels relate to firm productivity and policy stringency.

The main contribution of the paper is estimating the two abatement technology parameters. It reveals firms' current abatement technology level and provides a more precise prediction of emission reduction potential given the current technology level. It is important for policy markers to understand firms' abatement efficiency in order to improve policy effectiveness and efficiency. The paper's results suggest that firms have a higher efficiency on abatement in utilizing of inputs than green technology investment. As a result, a large number of firms would reduce emissions through sacrificing production instead of green technology adoption. The finding that there is a small emission intensity decrease even though there are large emission reductions reveals that the efficiency of the EU ETS for its long-term goal of cleaner production is limited. In addition, according to the decomposition analysis, the *Reallocation* effect dominates during all periods of the EU ETS regulation, while a larger *Investment* effect is observed during the period when EU ETS phases were shifting. In the end, the findings point out that the firms' heterogeneous response to policy matters, and the endogenous choice between *Reallocation* and *Investment* results in various abatement potential.

The large reallocating elasticity and *Reallocation* effect speak to the carbon leakage issue, which refers to emission reductions under the EU ETS that occur in the EU merely because production activities move to non-EU parts of the world without regulation. In theory, firms which compete in international markets could increase their imports or offshore their complete production, thus undermining the EU's contribution to a global reduction of carbon emissions. Studies of the energy-intensive industries, ranging from cement, steel, aluminium to refineries, chemicals or pup and paper, show that there are sectors for which the risk of carbon leakage is very likely, but would also need more in-depth analysis. In this paper, the results focusing on manufacturing sectors provide more evidence of carbon leakage issue during the EU ETS operating periods. For instance, some sectors at risk stand out: cement, basic mental (iron and steel and aluminium). Addressing the carbon leakage challenge is necessary to strengthen the ambition and credibility of the EU ETS as well as conveying a long term price signal. A common strategy used to limit leakage is to allocate free allowances for these high risk leakage sectors. Following that carbon leakage could be combated more efficiently using more flexible and targeted allocations, a revised EU ETS Directive has updated free allocation package in phase IV.

The results also have broader policy implications. The EU ETS forms an integral part of the European Union's roadmap to a low-carbon economy in 2050 (European Commission, 2011). Policy makers in New Zealand, the United States, Australia, China, Japan, South Korea, and elsewhere, can also learn from the EU ETS experience. So far, it appears that emissions reductions in the EU ETS have come largely from operational rather than technological changes. On average, policy stringency is far too generous on firms given the current abatement technology. Thus, firms could have done better for processing a cleaner production under the optimal policy stringency.

Extending the model to allow for more other abatement activities of firms would reveal further interesting facts. Activities such as energy switching, relocating productions geographically, and outsourcing the dirty intermediates are worthy of pursuit. Examining firms' permits trading behavior dynamically and deriving the optimal cap-and-trade policy are also worth further investigation. Future research might also look into other sectors, such as power and aviation sectors, by considering more firms' characteristics such as export status or whether firms are doing FDI.

Table 1.1.: Summary Statistics

Variable	Obs	Mean	Std. Dev	Min	Max
Emission Intensity ($\frac{e}{q}$)	10787	0.41	21.95	0	2651.74
Productivity (TFP_{ACF})	10787	8.28	68.08	0.01	4465.24
Policy Stringency (T)	10787	13.72	30.61	0	100
Variable (value divided by 1000000)					
Tangible Fixed Asset	10787	1060	9960	0	304000
Revenue	10787	2500	21800	0	727000
Employment Cost	10787	170	1360	0	43800
Working Capital	10787	225	2580	230	82600
Material Cost	10787	1530	16700	27	605000

Table 1.2.: Explaining Verified Emissions in the EU ETS

	(1)	(2)
log(tangible fixed assets)	0.049***	-0.051***
	(0.015)	(0.019)
log(operating revenue)		0.344***
		(0.042)
Year Fixed Effect	Yes	Yes
Firm Fixed Effect	Yes	Yes
Number of observations	18853	17567
Number of firms	2591	2441
R^2	0.04	0.12

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Standard errors are clustered on the firm level

Table 1.3.: Output Elasticities by Sector

Sector	N	Labor	Materials	Capital	Returns to Scale
Non-metallic Minerals (23)	4062	0.28	0.63	0.11	1.02
Pulp and Paper (17)	3092	0.34	0.52	0.19	1.05
Basic Metals (24)	880	0.20	0.64	0.10	0.94
Chemicals (20)	292	0.29	0.72	0.06	1.07
Petroleum and Coke (19)	169	0.34	0.87	0.16	1.37

Notes: Dependent variable is log of revenue and the proxy variable is material.

Table 1.4.: Comparison of ACF and LP Estimators

	(1)		(2)	
	Model		Model	
Parameter	ACF	LP	ACF	LP
β_{labor}	0.2737	0.2953	0.2227	0.2456
	(0.0515)	(0.0302)	(0.0412)	(0.0295)
$\beta_{capital}$	0.1982	0.1077	0.1133	0.1578
	(0.1349)	(0.0379)	(0.0278)	(0.0304)
$\beta_{material}$	0.3101	0.5878	0.5264	0.5565
	(0.0524)	(0.0972)	(0.1342)	(0.0525)
ln(TFP) (*mean*)	1.6009	1.4649	2.5419	0.9423
	(0.5589)	(0.4853)	(0.7333)	(0.6925)

(1): Dependent variable is revenue and proxy variable is material.

(2): Dependent variable is value added and proxy variable is emission.

Standard errors are clustered at firm level.

Table 1.5.: Estimated Markups by Sector

Sector	N	Method1	Method2
Non-metallic Minerals (23)	5203	1.58	1.31
Pulp and Paper (17)	4192	1.30	1.21
Basic Metals (24)	1162	1.21	1.12
Chemicals (20)	410	1.12	1.21
Petroleum and Coke (19)	232	1.27	1.09
All	11199	1.22	1.20

Notes: The median markup values are reported.

Table 1.6.: Explaining Emission Intensity in the EU ETS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OLS	OLS	OLS	IV	IV	IV	FD	FD	FD
log(productivity)	-0.140**	-0.137*	-0.166*	-0.150***	-0.108***	-0.161***	-0.207***	-0.238***	-0.317***
	(0.063)	(0.091)	(0.111)	(0.035)	(0.032)	(0.032)	(0.030)	(0.036)	(0.024)
log(policy)	-0.365***	-0.079***	-0.084***	-0.600***	-0.094***	-0.112***	-0.020**	-0.021***	-0.021**
	(0.104)	(0.015)	(0.015)	(0.044)	(0.017)	(0.017)	(0.009)	(0.009)	(0.009)
Country FE	Yes	No	No	Yes	No	No			
Industry FE	Yes	No	No	Yes	No	No			
Year FE	Yes	Yes	No	Yes	Yes	No			
Firm FE	No	Yes	Yes	No	Yes	Yes			
Country-Industry-Year FE	No	No	Yes	No	No	Yes			
TFP_{ACF}	✓	✓	✓	✓	✓	✓	✓		
TFP_{LP}								✓	
TFP_{DLW}									✓
N	10552	10552	10552	9874	9874	9874	9431	9431	9431
R^2	0.497	0.928	0.940	-	-	-	-	-	-

Notes: Standard errors in parentheses and clustered in firm level. I adopt log value of capital and depreciation as instrument variables.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 1.7.: Estimated Parameters

Parameter	Definition	Value (OLS)	Value (IV)	Value (FD)
β_1	productivity effect	-0.166	-0.161	-0.207
β_2	policy effect	-0.084	-0.112	-0.020
σ	elasticity of substitution	5.5	5.5	5.5
α	reallocating elasticity	0.846	0.847	0.826
ρ	green elasticity	0.020	0.012	0.042

Table 1.8.: Decomposition Coefficients (Elasticities)

(1)	(2)	(3)	(4)	(5)	(6)
ΔT	$\Delta(\widehat{1-\gamma})$	$\Delta\hat{f}$	$\Delta\frac{\hat{e}}{q}$	$\Delta\frac{\hat{e}}{q_{1-\gamma}}$	$\Delta\frac{\hat{e}}{q_f}$
1	$-\frac{\alpha}{\nu}$	$-\frac{\alpha(\sigma-1)}{\nu}$	$\frac{\alpha-\nu}{\nu}$	$-\frac{\alpha}{\nu}(\frac{1}{\alpha}-1)$	$\frac{\rho\alpha(\sigma-1)}{\nu}$
OLS	-0.92	-4.12	-0.08	-0.17	0.08
IV	-0.89	-3.99	-0.11	-0.16	0.05
FD	-0.98	-4.40	-0.02	-0.21	0.18

Notes: The values are in percentage change.

Table 1.9.: The Decomposition of Actual CO_2 Emission Intensity

Time Period	(1) $\overline{\Delta ln(\frac{e}{q})}$	(2) $\overline{\Delta ln(T)}$	(3) $\beta_2\overline{\Delta ln(T)}$	(4) $\overline{\Delta ln(1-\gamma)}$	(5) $\overline{\Delta ln(f)}$	(6) $\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}$	(7) $\overline{\Delta ln(\frac{e}{q})_f}$
Phase 1 (2005-2007)	-0.192	0.263	-0.005	-0.258	-1.157	-0.054	0.049
			[2.74%]			[28.24%]	
Phase 2 (2008-2012)	-0.373	-0.188	0.004	0.184	0.827	0.039	-0.035
			[-1.01%]				[9.32%]
Phase 3 (2013-2016)	-0.040	0.014	-0.0003	-0.014	-0.062	-0.003	0.003
			[0.70%]			[7.22%]	
Total (2005-2016)	-0.605	0.090	-0.002	-0.088	-0.396	-0.019	0.017
			[0.30%]			[3.07%]	

Notes: β_2 is estimated by the first difference, the value is -0.0207. The brackets of column (3) report the percentage value of $\frac{\beta_2\overline{\Delta ln(T)}}{\overline{\Delta ln(\frac{e}{q})}}$, the brackets of column (6) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}}{\overline{\Delta ln(\frac{e}{q})}}$, and the brackets of column (7) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_f}}{\overline{\Delta ln(\frac{e}{q})}}$.

Table 1.10.: The Decomposition of the Predicted CO_2 Emissions

Time Period	(1) ΔT	(2) ΔQ	(3) $\Delta \frac{\hat{e}}{q}_{total}$	(4) $\Delta \frac{\hat{e}}{q}_{1-\gamma}$	(5) $\Delta \frac{\hat{e}}{q}_{f}$	(6) $\Delta \hat{e}_{total}$	(7) $\Delta \hat{e}_{1-\gamma}$	(8) $\Delta \hat{e}_{f}$	(9) Δe_{total}
Phase 1 (2005-2007)	52.922	4.778	-5.927	-8.485	2.537	-62.897	-68.427	5.530	24.381
						[-23.67%]			[9.18%]
Phase 2 (2008-2012)	30.770	-6.468	-3.446	-4.933	1.475	-44.151	-45.781	1.630	-55.936
						[-16.62%]			[-21.05%]
Phase 3 (2013-2016)	1.947	41.675	-0.218	-0.312	0.093	38.812	36.883	1.929	26.077
						[14.61%]			[9.81%]
Total (2005-2016)	85.639	39.985	-9.592	-13.730	4.105	-68.237	-77.326	9.089	-5.478
						[-25.68%]			[-2.06%]

Notes: Columns (1)-(5) are percent change. Columns (6)-(9) are amount change in an unit of $MtCO_2e$.

Table 1.11.: Overview of CO_2 Emission Changes in the EU ETS in the Literature

	CO_2 emission reduction	Scope	Time
Ellerman and Buchner (2008)	100-200 $MtCO_2e$	EU, all sectors	2005-2006
Anderson and Di Maria (2011)	247 $MtCO_2e$	EU, all sectors	Phase I
Feilhauer and Ellerman (2008)	6.3%	Germany, manufacturing	Phase I
Wagner et al. (2014b)	13%	France, manufacturing	Phase II
Petrick and Wagner (2014)	25%	Germany, manufacturing	Phase II
Dechezleprêtre et al. (2018)	6%-19%	Four countries, manufacturing	Phase I, II

Table 1.12.: Explaining Emission Intensity in the EU ETS by Sector

Non-metallic Minerals (23)	OLS1	OLS2	OLS3	IV1	IV2	IV3	FD1	FD2	FD3
log(productivity)	-0.026	-0.106	-0.121*	-0.034	-0.103***	-0.120***	-0.232***	-0.354***	-0.413***
	(0.042)	(0.152)	(0.068)	(0.042)	(0.035)	(0.036)	(0.032)	(0.039)	(0.041)
log(policy)	-0.215***	-0.075***	-0.083***	-0.423***	-0.101***	-0.113***	-0.022***	-0.024***	-0.021***
	(0.030)	(0.021)	(0.021)	(0.042)	(0.022)	(0.023)	(0.009)	(0.009)	(0.008)
Country FE	Yes	No	Yes	Yes	No	Yes			
Year FE	Yes	Yes	Yes	Yes	Yes	Yes			
Country-Year FE	No	No	Yes	No	No	Yes			
Firm FE	No	Yes	Yes	No	Yes	Yes			
N	2518	3108	3092	2516	3074	3058	2376	2376	2376
R^2	0.711	0.923	0.926	-	-	-	-	-	-
Pulp and Paper (17)	OLS1	OLS2	OLS3	IV1	IV2	IV3	FD1	FD2	FD3
log(productivity)	-0.125**	-0.778***	-0.771***	-0.134**	-0.608***	-0.585***	-0.564***	-0.689***	-0.721***
	(0.068)	(0.220)	(0.227)	(0.069)	(0.083)	(0.088)	(0.089)	(0.085)	(0.079)
log(policy)	-0.347***	-0.073***	-0.083***	-0.602***	-0.057**	-0.082***	-0.039***	-0.042***	-0.043***
	(0.049)	(0.023)	(0.026)	(0.069)	(0.027)	(0.028)	(0.015)	(0.015)	(0.015)
Country FE	Yes	No	Yes	Yes	No	Yes			
Year FE	Yes	Yes	Yes	Yes	Yes	Yes			
Country-Year FE	No	No	Yes	No	No	Yes			
Firm FE	No	Yes	Yes	No	Yes	Yes			
N	1928	2337	2313	1926	2313	2290	1807	1807	1807
R^2	0.607	0.924	0.934	-	-	-	-	-	-
Basic Metals (24)	OLS1	OLS2	OLS3	IV1	IV2	IV3	FD1	FD2	FD3
log(productivity)	-0.204**	-0.140	-0.154	-0.106**	-0.142	-0.153*	-0.157**	-0.379***	-0.465***
	(0.080)	(0.156)	(0.155)	(0.080)	(0.144)	(0.127)	(0.097)	(0.111)	(0.111)
log(policy)	-0.199***	-0.089***	-0.092**	-0.245**	-0.076*	-0.136**	-0.029*	-0.025*	-0.023*
	(0.069)	(0.043)	(0.043)	(0.098)	(0.058)	(0.053)	(0.023)	(0.023)	(0.019)
Country FE	Yes	No	Yes	Yes	No	Yes			
Year FE	Yes	Yes	Yes	Yes	Yes	Yes			
Country-Year FE	No	No	Yes	No	No	Yes			
Firm FE	No	Yes	Yes	No	Yes	Yes			
N	588	701	673	587	693	664	548	548	548
R^2	0.725	0.908	0.933	-	-	-	-	-	-

$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

Table 1.13.: Estimated Parameters by Sector

Parameter	Definition	Value (OLS)	Value (IV)	Value (FD)
Non-metallic Minerals (23)				
β_1	productivity effect	-0.121	-0.120	-0.232
β_2	policy effect	-0.083	-0.113	-0.022
σ	elasticity of substitution	2.72	2.72	2.72
α	reallocating efficiency	0.883	0.881	0.808
ρ	green efficiency	0.024	0.007	0.125
Pulp and Paper (17)				
β_1	productivity effect	-0.771	-0.585	-0.564
β_2	policy effect	-0.083	-0.082	-0.039
σ	elasticity of substitution	4.33	4.33	4.33
α	reallocating efficiency	0.543	0.611	0.630
ρ	green efficiency	0.225	0.165	0.164
Basic Metals (24)				
β_1	productivity effect	-0.154	-0.153	-0.157
β_2	policy effect	-0.092	-0.136	-0.029
σ	elasticity of substitution	5.76	5.76	5.76
α	reallocating efficiency	0.855	0.850	0.861
ρ	green efficiency	0.014	0.004	0.028

Notes: Sector-specific markups are estimated here and the TFP is estimated based on ACF.

Table 1.14.: The Decomposition of Actual CO_2 Emission Intensity by Sector

Non-metallic Minerals (23)	(1) $\overline{\Delta ln(\frac{e}{q})}$	(2) $\overline{\Delta ln(T)}$	(3) $\beta_2\overline{\Delta ln(T)}$	(4) $\overline{\Delta ln(1-\gamma)}$	(5) $\overline{\Delta ln(f)}$	(6) $\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}$	(7) $\overline{\Delta ln(\frac{e}{q})_f}$
Phase 1 (2005-2007)	-0.183	0.204	-0.004	-0.200	-0.343	-0.047	0.043
			[2.46%]			[25.92%]	
Phase 2 (2008-2012)	-0.453	-1.171	0.026	1.145	1.969	0.272	-0.246
			[-5.69%]				[54.31%]
Phase 3 (2013-2016)	0.037	0.739	-0.016	-0.723	-1.243	-0.171	0.155
			[-44.05%]				
Total (2005-2016)	-0.598	-0.228	0.005	0.223	0.383	0.053	-0.048
			[-0.84%]				[7.99%]
Pulp and Paper (17)	(1) $\overline{\Delta ln(\frac{e}{q})}$	(2) $\overline{\Delta ln(T)}$	(3) $\beta_2\overline{\Delta ln(T)}$	(4) $\overline{\Delta ln(1-\gamma)}$	(5) $\overline{\Delta ln(f)}$	(6) $\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}$	(7) $\overline{\Delta ln(\frac{e}{q})_f}$
Phase 1 (2005-2007)	-0.319	0.349	-0.014	-0.335	-1.117	-0.197	0.183
			[4.26%]			[61.61%]	
Phase 2 (2008-2012)	-0.604	-1.320	0.051	1.268	4.224	0.744	-0.693
			[-8.52%]				
Phase 3 (2013-2016)	-0.270	0.482	-0.019	-0.463	-1.543	-0.272	0.253
			[6.96%]				
Total (2005-2016)	-1.193	-0.489	0.019	0.470	1.564	0.276	-0.257
			[-1.60%]				[21.50%]
Basic Metals (24)	(1) $\overline{\Delta ln(\frac{e}{q})}$	(2) $\overline{\Delta ln(T)}$	(3) $\beta_2\overline{\Delta ln(T)}$	(4) $\overline{\Delta ln(1-\gamma)}$	(5) $\overline{\Delta ln(f)}$	(6) $\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}$	(7) $\overline{\Delta ln(\frac{e}{q})_f}$
Phase 1 (2005-2007)	0.031	0.156	-0.005	-0.151	-0.720	-0.024	0.020
			[-14.34%]				[63.31%]
Phase 2 (2008-2012)	0.122	-0.759	0.02	0.737	3.510	0.119	-0.097
			[17.99%]			[97.41%]	
Phase 3 (2013-2016)	0.222	0.568	-0.02	-0.551	-2.624	-0.089	0.073
			[-7.43%]				[32.79%]
Total (2005-2016)	0.376	-0.036	0.001	0.035	0.166	0.006	-0.005
			[0.28%]			[1.50%]	

Notes: β_2 is estimated by the first difference, the value is -0.022, -0.039, and -0.029 respectively. The brackets of column (3) report the percentage value of $\frac{\beta_2\overline{\Delta ln(T)}}{\overline{\Delta ln(\frac{e}{q})}}$, the brackets of column (6) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}}{\overline{\Delta ln(\frac{e}{q})}}$, and the brackets of column (7) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_f}}{\overline{\Delta ln(\frac{e}{q})}}$.

Table 1.15.: The Decomposition of the Predicted CO_2 Emissions by Sector

Non-metallic Minerals (23)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ΔT	ΔQ	$\Delta\frac{\hat{e}}{q}_{total}$	$\Delta\frac{\hat{e}}{q}_{1-\gamma}$	$\Delta\frac{\hat{e}}{q}_{f}$	$\Delta\hat{e}_{total}$	$\Delta\hat{e}_{1-\gamma}$	$\Delta\hat{e}_{f}$	Δe_{total}
Phase 1 (2005-2007)	-20.893	-7.576	2.361	2.507	-0.146	49.667	50.007	-0.340	13.670
						[32.91%]			[9.06%]
Phase 2 (2008-2012)	-25.271	-30.981	2.856	3.033	-0.177	-91.637	-91.325	-0.312	-40.474
						[-60.73%]			[-26.82%]
Phase 3 (2013-2016)	-22.607	31.172	2.555	2.713	-0.158	86.801	88.921	-2.121	37.685
						[57.52%]			[24.97%]
Total (2005-2016)	-68.772	-7.384	7.771	8.253	-0.481	44.830	47.603	-2.773	10.882
						[29.71%]			[7.21%]
Pulp and Paper (17)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ΔT	ΔQ	$\Delta\frac{\hat{e}}{q}_{total}$	$\Delta\frac{\hat{e}}{q}_{1-\gamma}$	$\Delta\frac{\hat{e}}{q}_{f}$	$\Delta\hat{e}_{total}$	$\Delta\hat{e}_{1-\gamma}$	$\Delta\hat{e}_{f}$	Δe_{total}
Phase 1 (2005-2007)	73.398	-29.693	-6.019	-42.938	36.919	-24.280	-38.463	14.184	-11.568
						[-37.30%]			[-17.77%]
Phase 2 (2008-2012)	-44.086	-79.803	3.615	25.790	-22.175	-25.429	-17.067	-8.362	-25.751
						[-39.07%]			[-39.56%]
Phase 3 (2013-2016)	15.694	-18.949	-1.287	-9.181	7.894	-6.276	-4.412	-1.864	-3.021
						[-9.64%]			[-4.64%]
Total (2005-2016)	45.006	-128.445	-3.691	-26.329	22.638	-55.984	-59.942	3.958	-40.339
						[-86.01%]			[-61.98%]
Basic Metals (24)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ΔT	ΔQ	$\Delta\frac{\hat{e}}{q}_{total}$	$\Delta\frac{\hat{e}}{q}_{1-\gamma}$	$\Delta\frac{\hat{e}}{q}_{f}$	$\Delta\hat{e}_{total}$	$\Delta\hat{e}_{1-\gamma}$	$\Delta\hat{e}_{f}$	Δe_{total}
Phase 1 (2005-2007)	9.164	27.671	-1.246	-1.402	0.156	80.201	79.554	0.647	-56.452
						[26.81%]			[-18.87%]
Phase 2 (2008-2012)	-21.134	-43.805	2.874	3.234	-0.359	-168.399	-167.519	-0.881	-78.874
						[-56.30%]			[-26.37%]
Phase 3 (2013-2016)	20.732	13.318	-2.820	-3.172	0.352	21.211	20.353	0.858	21.244
						[7.09%]			[7.10%]
Total (2005-2016)	8.761	-2.816	-1.192	-1.340	0.149	-66.987	-67.612	0.625	-114.081
						[-22.39%]			[-38.14%]

Notes: Columns (1)-(5) are percent change. Columns (6)-(9) are amount change in an unit of $MtCO_2e$.

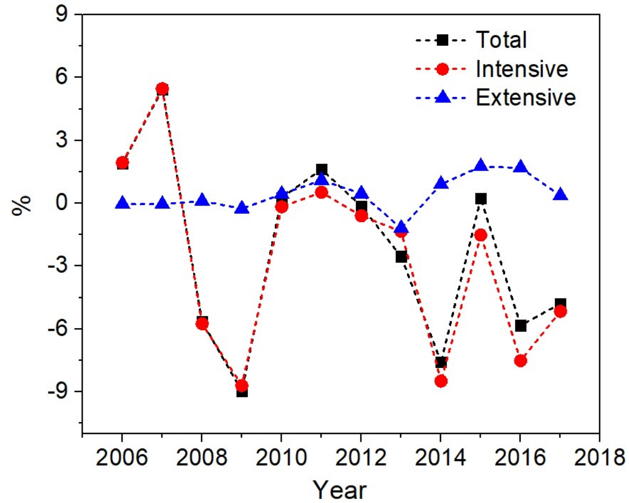


Figure 1.1.: Extensive Margin vs. Intensive Margin

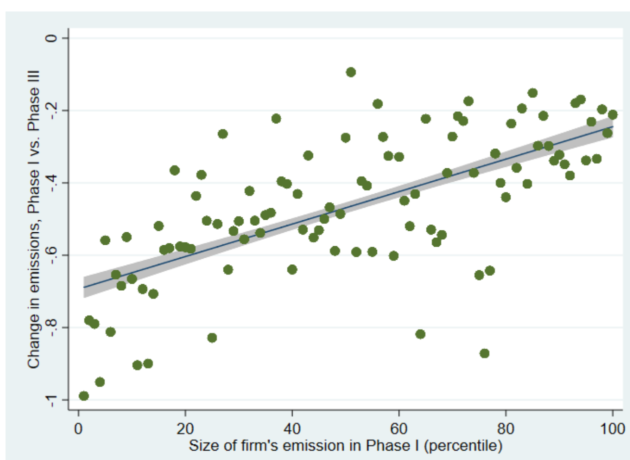


Figure 1.2.: Adjustments by Firm Size, Phase I vs. Phase III

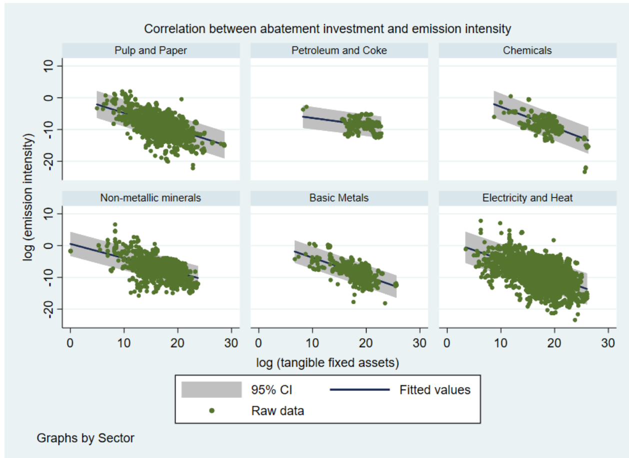


Figure 1.3.: The Correlation between Emission Intensity and Abatement Investment

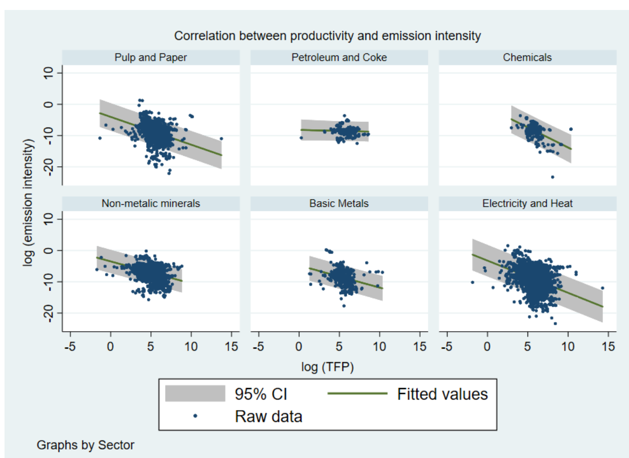


Figure 1.4.: The Correlation between Emission Intensity and Productivity

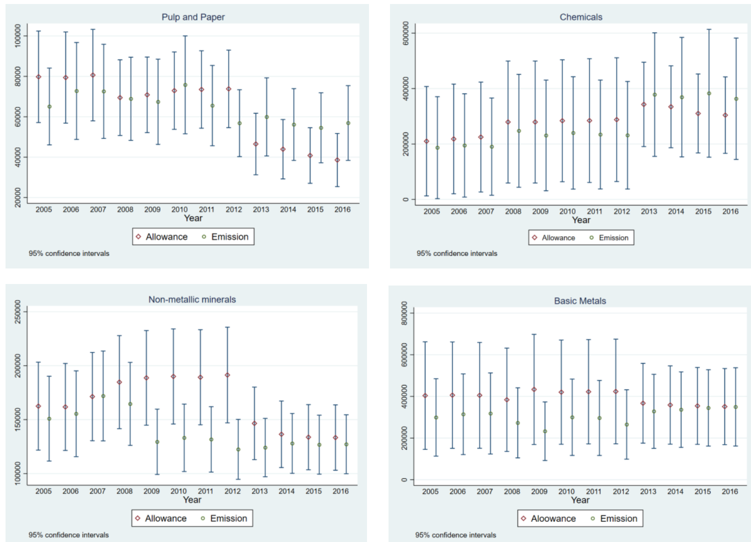


Figure 1.5.: The Mean Value of Allowance and Emission over Time by Sector

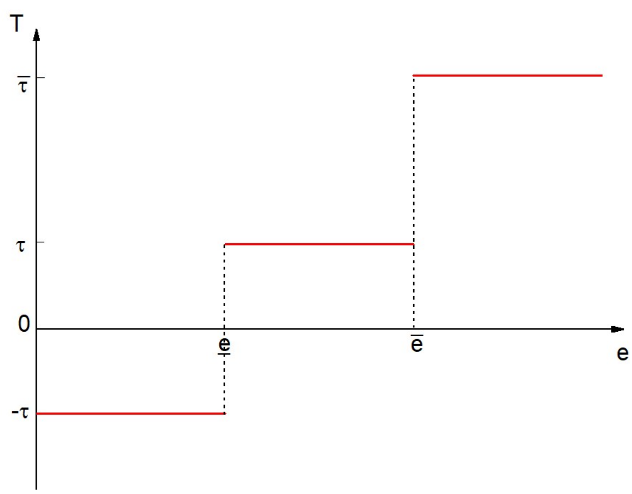


Figure 1.6.: The Marginal Compliance Cost of Emission

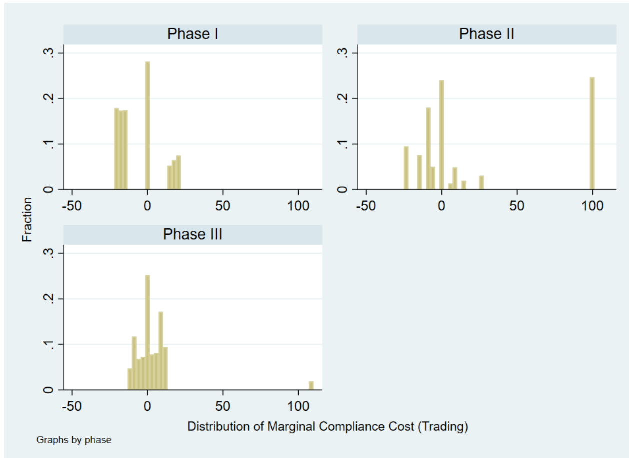


Figure 1.7.: Policy Stringency across Phases

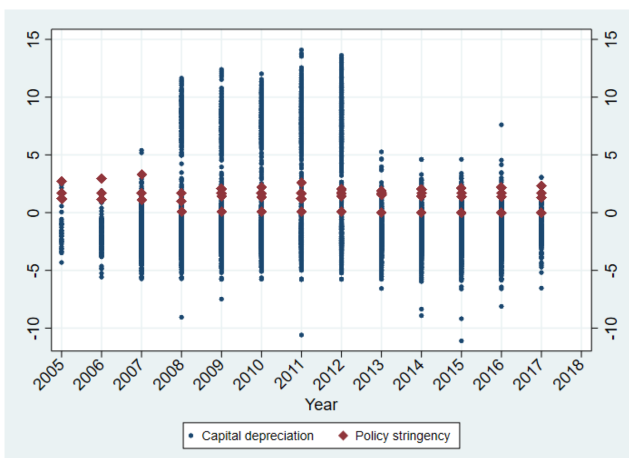
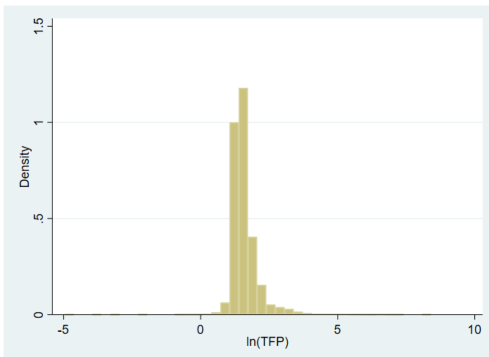
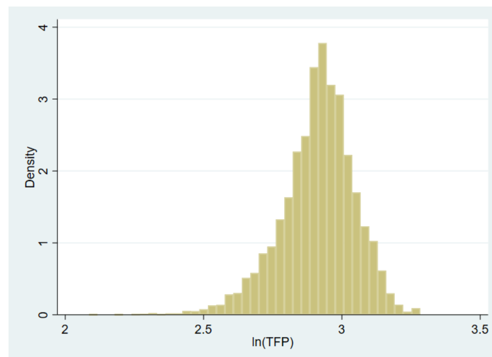


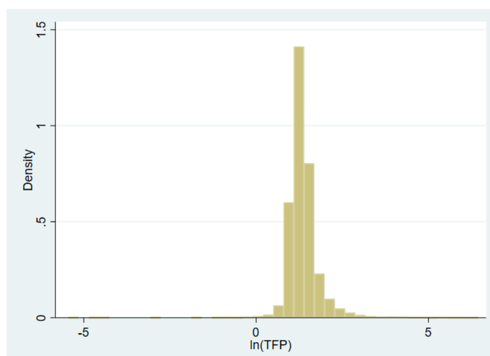
Figure 1.8.: The Variations of Capital Depreciation and Policy Stringency



(a) ACF



(b) DLW



(c) LP

Figure 1.9.: Estimated TFP Distributions by Three Approaches

2. GLOBAL EMISSION TRADING MARKET AND FIRMS' EMISSION TRADING PATTERNS: EVIDENCE FROM THE EU ETS

2.1 Introduction

Emission trading schemes have assumed an ever more salient role in ecological arrangement during the last couple of decades. In the US, examples of this trend include the Acid Rain Program, the Regional Greenhouse Gas Initiative (RGGI), and California's cap-and-trade program. Mexico, South Korea, the Canadian province of Nova Scotia, the Chinese province of Fujian, and the US state of Massachusetts have all recently created their own cap-and-trade programs to regulate greenhouse gas emissions (GHG). Other parts of the world, such as UK, Brazil, Thailand, and Philippines, are making moves toward launching their own. In 2019, the world's carbon markets grew 34% in value to $215 billion (Annual Global Market Report, World Bank). This number will likely grow much more in years to come, with so many scheduled or proposed initiatives under development.

The European Emission Trading Scheme (EU ETS) has played a major role in the global emission trading market. As a forerunner of a greenhouse gas trading system, the EU ETS can profess to be first in many aspects. It is the first cap-and-trade system for GHG, and it is by far the largest emissions trading market yet created. Additionally, it is the world's first multinational cap-and-trade system. Evaluating the current EU ETS scheme and directing reform for further phases are both based on understanding what firms are doing under the system. As more micro-level data are available and organized by each nation, putting together these datasets and documenting the trading patterns are the cornerstone for studies about the impact of the EU ETS.

The main purpose of this paper is to provide researchers with firms' detailed trading patterns with allowance and emissions based on my transaction-to-firm matching. The goal is to fully analyze the EU ETS accounts with their respective trading behaviors over time. My work is based on information provided by European Union Transaction Log (EUTL) and the World Carbon Market Database (WCMD). Importantly, I consider the full set of EU ETS regulated accounts available over three phases of the EU ETS. To the best of my knowledge, this study is one of the first to empirically analyze the trading behaviors and patterns of all ETS firms covering all three phases in the most complex and ambitious emissions tradable scheme ever developed. I use a unique dataset to investigate the permit trading behaviors of all types of trading in the market, including international offset permits. Additionally, some explanations of the identified trading patterns are provided in this paper.

Some interesting patterns are found in firms' transactions. First, a number of ETS firms did not participate in the European emission trading market and chose to trade allowances indirectly via third parties rather than directly.

Second, when focusing on transactions with different types in terms of trading partners, I find that the amount of transactions transferred within the same firm is sizable, especially in the first two phases of compliance. The majority of permits are traded between two parties nationally in phases I and II. The transactions amount drops significantly for non-government holders in phase III. Specifically, in phase III, both internal and national transactions decrease dramatically and the majority of trade is happening in the external and international markets.

Third, the permit transactions are clustered at two months of each year: April and December. April is the end of compliance year, when firms report and surrender permits. December is the end of calendar year, when most of the permit futures or forwards are mature and settled. Firms optimize their allowance portfolios around the compliance month so that the internal transfers are more concentrated at the end of compliance year. In contrast, firms' trade, especially external and international transactions, mostly depend on permit prices and are more clustered at the end of calendar year.

Fourth, for most firms, the participation is limited to a small amount of transactions per compliance year, and the patterns are consistent in each transaction group. For instance, conditional on each transaction type, the majority of firm-by-year transactions transact at most 0.5 million tons of permits across all phases.

Fifth, more than 60% of firms conduct at most five transactions per year, and only around 10% of firms transact more than 50 times yearly in internal transfer, national trade, and external trade. Firms participate in international market trade more often, with the majority of firms having more than five transactions and 20% of firms trading more than 50 times per year.

I also analyze the historical market prices of European certificates (EUAs) and International offsets (CERs). I observe that EUA prices are quite volatile over time, with the highest price up to 30 euros and the lowest price down to near 0 euro. Focusing on phase III, EUA prices rose mildly from 2013 to 2015, but have shown a steep rise since 2018. Daily price data of CERs and EUAs available from Intercontinental Exchange show that CERs have always traded at a lower price from EUAs. According to the calculation of Naegele (2018), this price spread allowed firms to achieve considerable savings, reaching 217.4 million euros for the largest firm. Due to the price difference, firms have a strong motivation to get the offsets. However, these offsets are project-based and limited. I observe that larger and multinational firms obtain offsets mostly in the trading market.

The main contribution of this paper is to document the emission trading patterns in the EU ETS with all regulated firms and all phases including international offsets. In addition, the paper reviews all existing and proposed emission trading systems in the world with discussion of their main features in order to better understand the external trading between two different emission trading systems and the availability of offsets trading.

The rest of the paper is organised as follows. Section 2 documents background of ETS focusing on the global emission trading programs and the development of firms' emission trading options in the EU ETS over three phases. Section 3 introduces the data source. Section 4 presents identified firms' emission trading patterns with potential explanations. Section 5 concludes with discussing the findings in light of the broader empirical literature.

2.2 Background

2.2.1 Global Emission Trading Systems

Emission trading systems are developed as an expedient to place a price on greenhouse gas emissions by nations and regions around the world. Such schemes are now in place in Europe, North America, Oceania, and some parts of Asia. South America and more regions in Asia are in the process of adopting the scheme.[1] With the rapid establishment of ETS in other parts of the world, emission reduction efforts under the Kyoto Protocol guidelines seem to have shifted from the global level to national and local levels. External trading, defined as transactions between two registries in different countries, accounts for 33% (11676 million tons) of the total traded CO_2 permits during 2005-2016. This percentage portion expands to 82% in the first half of phase III.[2] To better understand the external trading between different regional ETS systems, I provide an overview of existing and selected emerging greenhouse gas trading schemes worldwide in this subsection focusing on the availability of banking or borrowing, as well as the availability of international offset credits. Table 2.1 summarizes the main features of all existing and proposed emission trading systems in the world.

[1]ETS in force: European Union, USA (California), Canada, Swiss, Kazakhstan, New Zealand, Japan, South Korea, China (some provinces); ETS scheduled: Mexico, Ukraine; ETS considered: USA (Washington, Oregon, Virginia), Colombia, Brazil, Chile, Russia, Turkey, Thailand, Vietnam

[2]Refer to Table 3

Globally, emission trading systems have been operated in 36 national and 15 subnational jurisdictions. There are 6 regional emission trading systems scheduled to be implemented. Additionally, more countries, such as UK, Brazil, Chile, Turkey, Indonesia, Thailand, Philippines, Vietnam, and Pakistan, are considering adopting ETS in the near future. The European emissions trading scheme is the world's largest carbon market, covering 31 countries that emit over 40 billion tons of GHG each year. The ETS in California and Quebec cover sectors emitting nearly half a billion tons of GHG. The programs in Asian countries, such as Korea and China, regulate sectors that emit half a billion tons and over one billion tons of CO_2, respectively. All ETS cover emissions focusing on carbon dioxide, and some of them cover all GHG.

Although both US and Canada have failed to establish national emission trading systems, they have received the necessary political support in some areas. In United States, the Regional Greenhouse Gas Initiative (RGGI), a joint emission trading scheme, is established by nine states targeting to power and heat industries. Starting in 2014, Canadian provinces Quebec and Nova Scotia linked their regional systems with the RGGI in US. Following the EU ETS, the development of ETS in other parts of the world increases rapidly after 2010, especially in Asian countries. It is notable that China has adopted the ETS on a province or city level staring from 2013 and is on the way of developing a China National ETS, which will be seen as a strong dynamic toward the EU ETS. Elsewhere in Asia, Japan is operating two regional-level emission trading schemes, but unlike China, is not planning a national ETS. Australia was planning a national ETS in 2013, but this ended up being abandoned due to a change in government.

Banking provides a way for the regulated firms to save excess allowances for later compliance. Borrowing allows the regulated firms to "borrow" allowances from future years. Although they help avoid permit price spikes, both banking and borrowing bring difficulties of operation and management. In order to deal with the issue of banking and borrowing, global emission trading systems have developed and adopted various additional elements and conditions on banking and borrowing. Banking is allowed for all global ETS, with conditions that vary between regions. For instance, in Kazakhstan, banking is possible within one trading period but not allowed between trading periods. Borrowing is not possible in most regional ETS, even in the flagship EU ETS, due to concerns regarding lagging emission compliance and the complexity of operation. In the Korean ETS, borrowing is allowed only within a single trading phase.

In order to coordinate international efforts of emission reduction and to lower abatement cost for EU-based companies, starting from 2008, the EU linked the EU ETS to the international framework established by the United Nations Framework Convention on Climate Change and the Kyoto Protocol. According to these international conventions, some suitable projects are established. These projects are low-carbon energy projects, such as wind farms, solar arrays, or projects to reduce emissions from forestry. These projects save emissions in unregulated parts of the world, "non-Annex I" countries, which are the suppliers of the international offset permits. In practice, the international offsets are mostly from China and India. All the emission saving projects are organized and verified through Clean Development Mechanism (CDM) or Joint Implementation (JI). And currently, CDM is the largest international offsets market in the world. The last column in Table 2.1 records whether the ETS can obtain the international offsets or not. All emission trading programs in the world allow members to obtain international offset credits, but most of them set quantitative limits for trading. These limits vary from region to region. In contrast, credits from four offset types are allowed in the Tokyo ETS, with no quantitative limits for trading. Canada and Kazakhstan have a similar absence of quantitative limits.

2.2.2 The European Union Emission Trading Systems

The EU ETS was launched in 2005 with the goal of reaching the EU reduction target set during the Kyoto Protocol in a cost-effective way. The long-term objective is to promote the adoption of low-carbon technologies. However, the effectiveness of the EU ETS and its corresponding influence on the carbon market is much debated. Various reform plans have been proposed to improve the current trading system. Major reform targets include exploring alternative ways of allocating target emission permits, designing trading caps, and expanding the international offset market. The central mechanisms to reach these targets are based on allowance allocation and emission permits auction. The allowance allocation, auctioning, and the international offset permits are part of a complex regulatory framework. In this subsection, I explain each concept with the development of the EU ETS over phases.

Grandfathering and Auctioning

Generally, the EU Commission issues EU emission allowances (EUAs) that sum up to the overall EU emission cap each year. Regulated firms have to report their emissions and submit (surrender) permits offsetting their emissions at the compliance period each year. Surrendered permits disappear from the market, and unused permits remain valid in subsequent years (banking).

In phase I, all permits are distributed to firms for free according to their historical emission levels, which is called *grandfathering* approach of allocation. With the development of the EU ETS, starting in phase II, the auction approach has been increasingly applied to allocate emission permits, and appears to be a preferable method among regulators due to its potential efficiency improvement. The permits that are allowed to auction increased from 10% in phase II (2008-2012) to 57% in phase III (2013-2020) (Auction Report 2018, European Commission). The *grandfathering* quotas initially set by the EU ETS are gradually decreasing. Specifically, in the power sector, there is no freely allocated allowance starting in phase III. All emission permits need to be acquired from auctioning either from the European Commission or from other regulators.

International Offset Permits

Understanding firms' trading patterns in the international offset market is fundamental for policy makers to consider whether the international offset market is worthwhile because a worldwide carbon leakage is potentially enhanced by the international offsets trading.

Starting in phase II, firms are granted international offsets from countries outside the EU through a project-based scheme. These alternative international offsets named Certified Emissions Reductions (CERs) or Emission Reduction Units (ERUs), are generated from CDM and JI, accordingly. As a result, firms have an option to obtain and utilize international offsets directly from the original party by investing in CDM or JI projects (primary CERs or ERUs) or indirectly from the marketplace (secondary CERs and ERUs). The verified international offset permits can be used to justify emissions in EU countries. Different from EU permits, there is no free distribution of these offsets, so firms need to actively acquire them through the international market. The EU permits and offsets are perfect substitutes, and this substitution was attractive because offset permits are generally cheaper than EU permit prices. The CDM mechanism has already registered more than 1650 projects since 2008 amounting to more than 2.9 billion tons of CO_2, with most of the generated CERs coming from China and India. However, there are some specific rules that validate the projects so that the supply of CERs have larger uncertainties than EUAs.

International offsets are permitted for use in the EU ETS. However, there are some specific rules that dictate how many and what kind of offsets can be used for compliance. The overall use of international offset permits is limited to 50% of the EU wide reductions over the period 2008-2020. Some regulators are sensitive to the sustainability credentials of the offsets due to their environmental and corporate social responsibility policies. Firms are balancing the higher entry and transaction cost of the international permit market with the overall compliance benefits of utilizing the international permits (Guide to EU ETS Offsets).

2.3 Data

The descriptive analysis is based on two data sources. The first data source is the European Union Transaction Log (EUTL). There are three main datasets available on the EUTL that can be used to assess permit transfer patterns: Operator Holdings Accounts (OHAs), Person Holding Accounts (PHAs), and the EUTL Transfer dataset. This paper uses the EUTL Transfer dataset. The EUTL Transfer dataset includes information regarding the installations covered by the scheme, the respective account holders, and in particular data on account-level emission permit transactions. Much detailed transactions information can be obtained, such as account type, market type, number of EUAs transacted, transaction time, and basic information on both parties in a transaction. The EUTL Transfer dataset contains dynamic data on the flow of permits, which are currently published with a delay of three years. The transactions of all regulated installations with an account were available for the period 2005-2016. At the time this study was performed, the most recent transactions with a complete calendar trading year were recorded at the end of December 2016. Therefore, I have excluded all transactions performed in 2017, as the compliance period for the year 2017 finished in April 2017.

The second data source includes firm-level emissions data from the World Carbon Market Database (WCMD), which contains detailed firm-level emission and allowance information aggregated from different carbon trading markets. The WCMD dataset contains regulated installations' emission and free allowance at the individual firm level, which helps to identify firms regulated by the EU ETS. The account-level data on transactions were aggregated to the firm level by year to facilitate the following descriptive analysis.

2.4 Descriptive Analysis

A wide range of firms' emission trading patterns are presented in this section based on my transaction-to-firm matching. Note that the analysis includes all regulated firms that have a trading account and a transaction in EUTL from 2005 to 2016.

Transactions by Holding Account I first focus on the transaction accounts recorded in EUTL. There are four general account types: government holding account, person holding account, operator holding account, and other. Government accounts are involved in distributing free allowance to registries. Third parties, such as financial brokers and trading consultants, are registered as person holding accounts. All inter-firm transactions are carried out with operator holding accounts. As reported in Table 2.2, I observe that 69.4% of transactions amount are transacted within government accounts, which reveals a large amount of allowance allocation. 14.17% of transactions are through person accounts, and this percentage is almost twice as large as the transactions directly delivered among firms. It indicates that a large number of ETS firms did not participate in the European emission trading market and chose to trade allowances indirectly via third parties rather than directly. In addition, third parties make more frequent transactions but smaller amounts of permits than government bodies.

Transactions by Category of Trading Partners The total permit transaction volume is 44.1 billion tons of CO_2. 13% (5.7 billion) of the transactions are between the EU Commission and installations for the purpose of free allowance allocation. Due to the surrender activity is in installation level, I also observe intra-firm transfers such that around 10% (4.6 billion) of the transactions are transferred within the same firm, recorded as Internal in Table 2.3. Internal transfers capture the transactions between two installations owned by the same firm. The majority of transactions are executed between two different holders, comprising 77% (34.2 billion) of the total transactions. I further classify transactions between two different holders by establishing three subcategories. National represents transactions between two different account holders within the same registry (country): for instance, German firm A purchases a number of permits from German firm B. External represents transactions between two different account holders in different registries (countries): for example, German firm A purchases a number of permits from French firm B. International includes transactions of international offset permits generated from the Clean Development Mechanism (CDM): firm A obtains a number of offset permits through CDM from the unregulated parts of the world.

The transactions data with identified account holders reveal several interesting patterns. Firms in our sample have received yearly allocations of 2064, 1956, and 884 million EUAs for the phase I, phase II. and phase III compliance periods, respectively. Accounts controlled by the firms in our sample acquired EUAs for a total of 1,278 million tons of CO2 during all compliance years from 2005 to 2016. However, once we account for different types of transactions, we find (1) Internal transfers are sizable, especially in the first two phases of compliance. There are 1058 million tons of CO2 internal transfers in phase I, accounting for 41% of the total transactions in phase I. The proportion of internal transfers decreases to 11% in phase II. We observe a large number of internal transfers in phase I because phase I is the pilot learning-by-doing phase; account holders practice transactions internally not only for compliance requirements but also to become familiar with the trading systems. (2) The majority of permits are traded between two parties nationally in phases I and II. The national transactions, with 1505 million tons of CO2 in phase I and 16531 million tons of CO2 in phase II, make up 59% and 54% of total transactions in phases I and II, respectively. (3) The amount of transactions shows major drops for non-government holders in phase III. Specifically, both internal and national transactions decrease dramatically, and the majority of trade happens in the external and international markets in phase III. There are several reasons the amount of transactions decreases during phase III. First, the issue of over-allocation in the first two phases results in firms pursuing self-compliance rather than purchasing permits from trade. Second, government proposes to recall allowances from back-loading; therefore, a large number of transactions are identified as being between firms and government accounts instead of operator holding accounts, which record transactions between firms. Third, many firms may choose to bank the permits instead of trade. After experiencing the first two phases of EU ETS, firms should have gained much experience in strategic trading. They may get more involved in banking or borrowing during a more mature and experienced phase III period. Since phase III lasts until 2020, if firms have excess permits, firms are more likely to bank permits in the early years of phase III and use them for later years when facing tighter cap and allocation.[3]

Transactions through A Year I next consider the distribution of EUA trading by the firms in our sample over time. As shown in Figure 2.1, we observe that the permit transactions are clustered in the month of April, the end of compliance year, and in the month of December, the end of calendar year.[4] When separating the transactions into internal transfer and trade in Figure 2.2, we observe that internal transfers are more concentrated at the end of compliance year. In contrast, inter-firm transactions are more concentrated at the end of calendar year. As demonstrated in Figure 2.3, among inter-firm transactions, national transactions are more pronounced at the end of compliance year. External transactions are clustered in December, suggesting a lot of transactions between firms in different countries are in the form of futures or forward contracts. Because December is the time when most of these contracts are mature. The timing of international offset transactions heavily depends on the supply side of offsets. Since they are project based, firms need to check the verified permits and issuance from a different international offset market through projects over time.

Firm Level Transaction Quantities I also look at firms' transaction quantity distributions in each group. For most firms, the transaction amount is limited per

[3]The cap decreases by 7.4% yearly in phase III.

[4]Every year, operators must submit an emissions report. The data for a given year must be verified by an accredited verifier by March 31 of the following year. Once data are verified, operators must surrender the equivalent number of allowances by April 30 of that year.

compliance year, and the patterns are consistent in each transaction group. Only several firms purchase extremely large amount of permits thus driving the large total transaction amount. For instance, conditional on each transaction type, the majority of firm-by-year transactions transact at most 0.5 million tons of permits across all phases. A small number of firms trade in the international market and very few firm-by-year transactions are less than 10 thousand tons of permits once in international market. As shown in Figure 2.4, the distributions of internal transfers, national trades, and external trade are similar, with 20-40% firm-by-year transactions are less than 0.01 million tons of permits. However, in the international offset market, this number decreases to 7%. This indicates that the regulated firms may not cover the average cost of transactions if purchasing a very small amount of permits. As a result, a group of small firms may not choose to enter the international market.

Firm Level Transaction Frequencies Figure 2.5 presents firms' trading frequencies per year. It demonstrates that conditional on each transaction group, more than 60% of firms conduct at most 5 transactions per year. Around 10% of firms transact more than 50 times yearly in internal transfer, national trade, and external trade. Aside from these three types of transactions, firms participating in international market trade more often, with the majority of firms having more than 5 transactions and 20% of firms trading more than 50 times per year.

EUA Price Trend Although this study does not link the price data with transactions of EUTL due to some limitations, I still provide an analysis of the historical prices of EUA. The historical futures prices of EUAs are reported in Figure 2.6. The price patterns reveal that price is quite volatile over time, with the highest price up to 30 euros and the lowest price down nearly to 0 euro. The EUA price went down to around 0 in the period of recession, during which the main drivers of low prices were reduced production and over-allocated free allowance. The price trend in phase II decreases largely due to the over-allocation issue. In addition, the EUA prices are more volatile in phase II because of the introduction of international offset permits.

I also provide the EUA prices covering all years in phase III. In the early years of phase III, EUA prices rise mildly, from 5 euros in 2013 to 8 euros in late 2015. However, during the second half of phase III, we observe a sharp climb of prices up to 29 euros in the middle of 2019. Especially, the EUA prices rise beyond double-digit levels and more than triple since the start of the year 2018. Here are several factors which could explain this steep rise in EUA prices since 2018. First reason is tighter policy in terms of cap. The emission cap has reduced in phase III with an annual decline of 1.74%, and this number increases to 2% in planned phase IV. Also, there is a reform puts a tighter policy. The revised policy base on Market Stability Reserve (MSR) states that 265 million allowances should be taken off the market over the first eight months of 2019. Additionally, low-carbon generation facilities across the EU reduced production during the 2018 summer period. Instead, they are in favor of more polluting conventional thermal generation, which in turn increased demand for emission quotas. In the end, the steady increase in industrial output in the EU since 2017 has logically implied a rise in demand for quotas and contributed to the perception of a tightening market. So overall, this steep price rise is due to tighter policy and larger demand of permits.

2.5 Conclusion

The carbon market is currently considered as the fastest growing markets, and the European Union Emissions Trading Scheme (EU ETS) has played a major role in pushing it up to this level. Following the EU ETS, there are several ETS programs have established in countries such as China, New Zealand, and South Korea in order to complement the existing UNFCCC-based mechanisms and stimulate further actions to support domestic policy objectives. In this paper, I provide an overview of all existing and proposed global emission trading systems, indicating their features related to trading.

Given the development of the EU ETS, I also document the key concepts of the emission trading system including international offsets. Based on the EUTL data, I analyze and deliver a wide range of firms' emission trading patterns by country, trading partners, and market type, including transactions amount, transactions frequency, firms' transaction distribution, and EUA price information. Some explanations of the identified trading patterns are provided in the paper. My study covers all regulated firms over three phases of the EU ETS. Compare with other data work and review papers, Zaklan (2013) focuses on firms' trading patterns of two years in phase I, when firms do not have many trading options. Guo et al. (2018) investigate the effect of verified emission announcements on firms' purchasing and selling behaviors by focusing on trade amount over first the two phases of EU ETS. Sanin et al. (2015) highlight the volatility dynamics of EUA prices by analyzing the price data during phase I. They conclude the different fundamentals before and after 2008 and emphasize the trade-off between providing information effectively and promoting market stability. Few works classify transaction categories by trading partners, and studies looking at international offsets trading patterns are even more scarce.

This paper is intended to serve as a background for researchers to investigate emission trading using the EUTL Transfer dataset. In addition, some parts of my study can contribute to future research about firms' trading behaviors focusing on EUA price and market power, or firms' trading behaviors including third parties and their interactions with ETS installations.

Table 2.1.: Global Existing and Proposed ETS

Existing ETS	Year Established	Covered Gases & (Percentage)	Year Emission	Banking	Borrowing	Offsets
Canada-Nova Scotia	2019	All GHG (80%)	15.9 $MtCO_2e$	No	No	Yes
Canada-Quebec	2013	All GHG (82%)	78.7 $MtCO_2e$	Yes	No	Yes, but limited
China-Beijing	2013	CO_2 (40%)	188.1 $MtCO_2e$	Yes	No	Yes, but limited
China-Chongqing	2014	All GHG (50%)	300 $MtCO_2e$	Yes	No	Yes, but limited
China-Fujian	2016	CO_2 (60%)	240 $MtCO_2e$	Yes	No	Yes, but limited
China-Guangdong	2013	CO_2 (60%)	610.5 $MtCO_2e$	Yes	No	Yes, but limited
China-Hubei	2014	CO_2 (45%)	463.1 $MtCO_2e$	Yes	No	Yes, but limited
China-Shanghai	2013	CO_2 (57%)	297.7 $MtCO_2e$	Yes	No	Yes, but limited
China-Shenzhen	2013	CO_2 (40%)	83.45 $MtCO_2e$	Yes	No	Yes, but limited
China-Tianjin	2013	CO_2 (55%)	215 $MtCO_2e$	Yes	No	Yes, but limited
EU	2005	CO_2, N_2O, PFCs (45%)	4323 $MtCO_2e$	Yes	No	Yes, but limited
Japan-Saitama	2011	CO_2 (18%)	36.6 $MtCO_2e$	Yes	No	Yes, but limited
Japan-Tokyo	2010	CO_2 (20%)	64.8 $MtCO_2e$	Yes	No	Yes
Kazakhstan	2013	CO_2 (50%)	353.2 $MtCO_2e$	Yes	No	Yes
Korea	2015	All GHG (70%)	709.1 $MtCO_2e$	Yes	Yes	Yes, but limited
Mexico	2020	CO_2 (37%)	733.8 $MtCO_2e$	–	–	Yes, but limited
New Zealand	2008	All GHG (51%)	81.0 $MtCO_2e$	Yes	No	Yes, limited from 2015
Swiss	2008	All GHG (10%)	47.2 $MtCO_2e$	Yes	No	Yes, but limited
USA-California	2013	All GHG (80%)	424 $MtCO_2e$	Yes	No	Yes, but limited
USA-Massachusetts	2018	CO_2 (12%)	73.3 $MtCO_2e$	Yes	No	No
USA-RGGI	2009	CO_2 (18%)	463.6 $MtCO_2e$	Yes	No	Yes, but limited

Proposed ETS	Commitment Year	Covered Gases & (Percentage)	Year Emission	Banking	Borrowing	Offsets
China National	2018	CO_2 (30%)	10976 $MtCO_2e$	Yes	No	Yes, but limited
Colombia	2018	–	237 $MtCO_2e$	–	–	–
Montenegro	2020	–	3494 $MtCO_2e$	–	–	–
Ukraine	2017	–	320.6 $MtCO_2e$	–	–	–
USA-Pennsylvania	2019	–	264.4 $MtCO_2e$	–	–	–
USA-Virginia	2017	–	136 $MtCO_2e$	–	–	–

The base year of Year Emission is 2017

Table 2.2.: Transactions by Holding Account

Account Type	Account ID	N of Transactions	Transactions Amount	Percentage
Government hold	100	325,389	118478.60	69.40
Person hold	121	354,902	24187.22	14.17
Operator hold	120	94,704	12807.32	7.50
Others	110, 230	6,628	15242.12	8.93

Table 2.3.: Permit Allocation and Trading Patterns for Identified Firms

	Allocation	Internal	National	External	International
2005	2,053	82	196	0	0
2006	2,029	533	692	0	0
2007	2,110	443	617	0	0
2008	1,921	438	2023	1137	126
2009	1,929	618	5996	3540	80
2010	1,953	758	3562	2460	63
2011	1,971	955	2933	2011	180
2012	2,006	698	2017	783	159
2013	978	39	47	1016	107
2014	905	7	10	286	31
2015	846	7	4	184	13
2016	808	11	52	259	68
Phase I	6192	1058	1505	0	0
Phase II	9780	3467	16531	9931	608
Phase III	3537	64	113	1745	219
Sum	19509	4589	18149	11676	827

Notes: The values are in the unit of million tons of CO_2

The account types are included: operator holding account and person holding account

The international permits are generated from Clean Development Mechanism (CDM)

Table 2.4.: Permit Allocation and Trading Transactions by Registries

Registry	Transactions		Allocation
	Quantity	Frequency	
United Kingdom	11360	59595	1567
France	8496	183591	1177
Germany	4931	40618	3585
Denmark	3026	42521	233
Italy	3012	21862	1671
Netherlands	2445	19811	676
Spain	1126	17972	1244
Greece	896	2220	569
Czechia	779	7163	833
Romania	723	2865	512
Austria	642	7610	262
Poland	521	8817	1814
Finland	497	6720	355
Bulgaria	372	1246	
Sweden	362	9181	242
Belgium	303	2144	380
Norway	287	2281	
Ireland	273	1564	153
Hungary	181	1735	231
Slovakia	165	2196	280
Estonia	117	618	135
Portugal	110	1731	262
Liechtenstein	102	2430	
Slovenia	95	1082	70
Lithuania	79	722	83
Latvia	26	360	28
Czech Republic	4	49	11
Cyprus	4	30	36
Luxembourg	3	200	24

The values are in the unit of million tons of CO_2

All market types are included (internal, national, external and international)

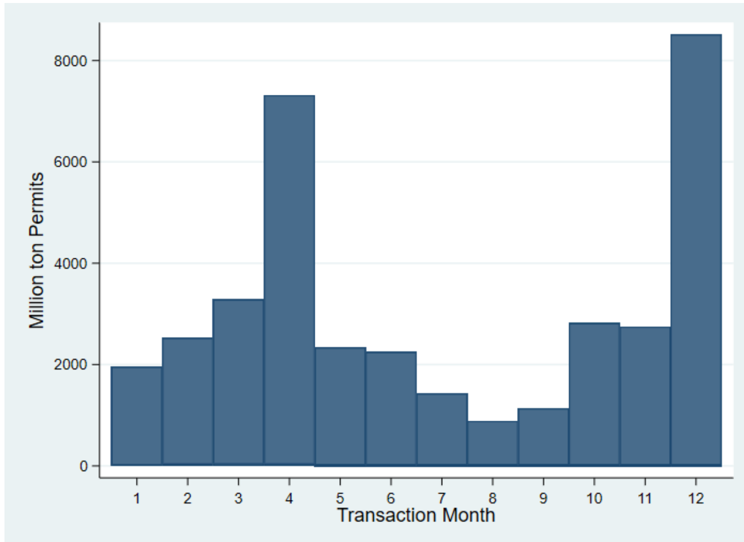


Figure 2.1.: Total Transactions by Months

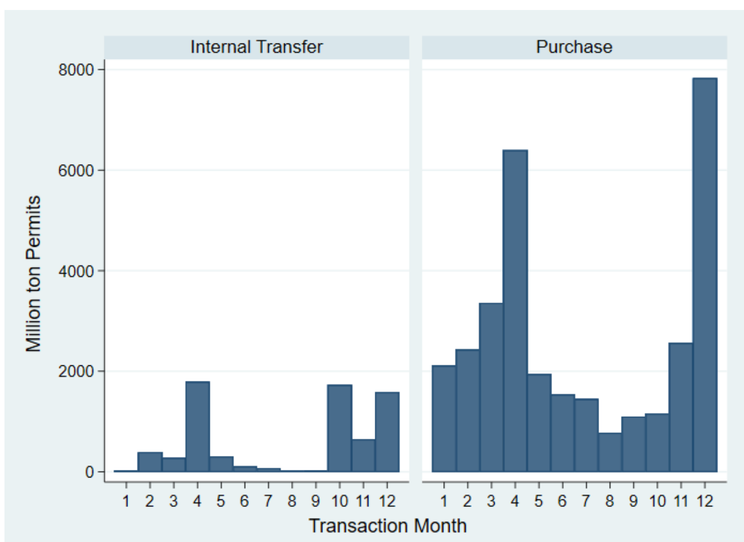
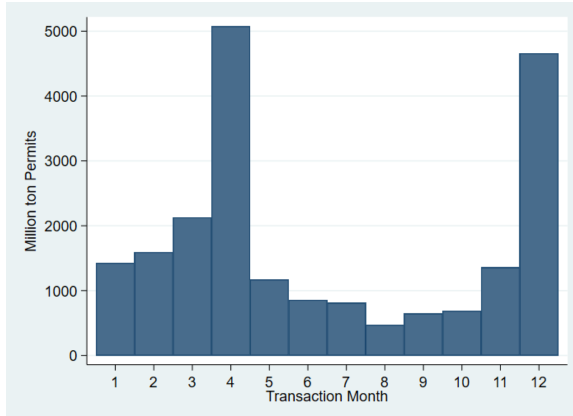
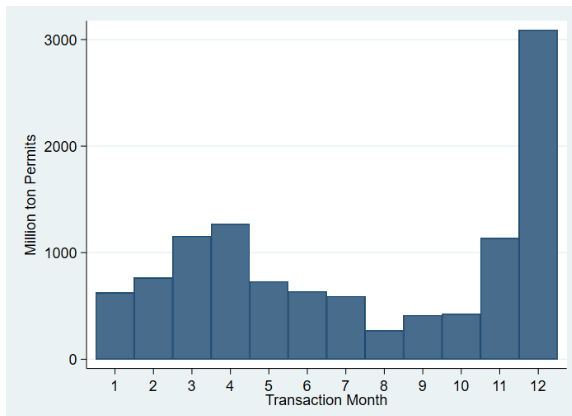


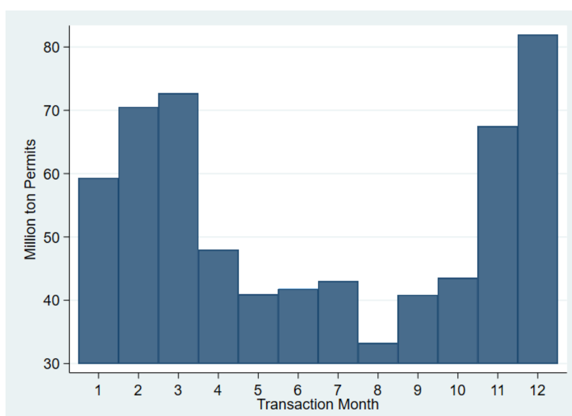
Figure 2.2.: Transactions by Months and Type



(a) National

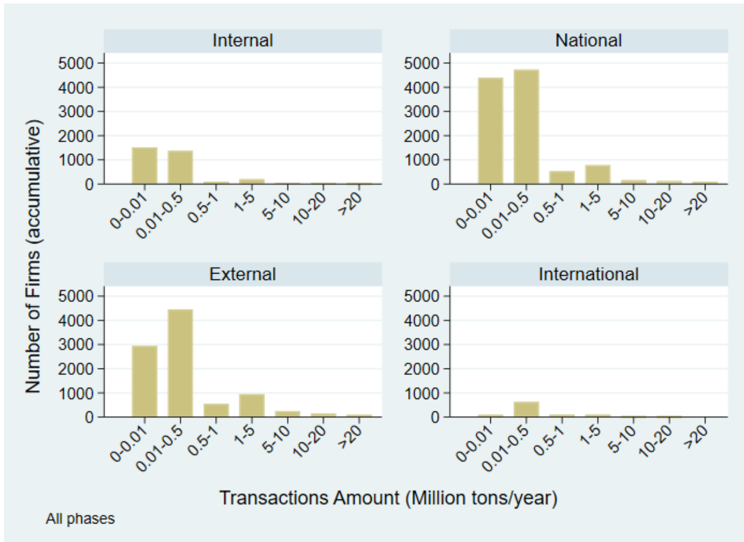


(b) External

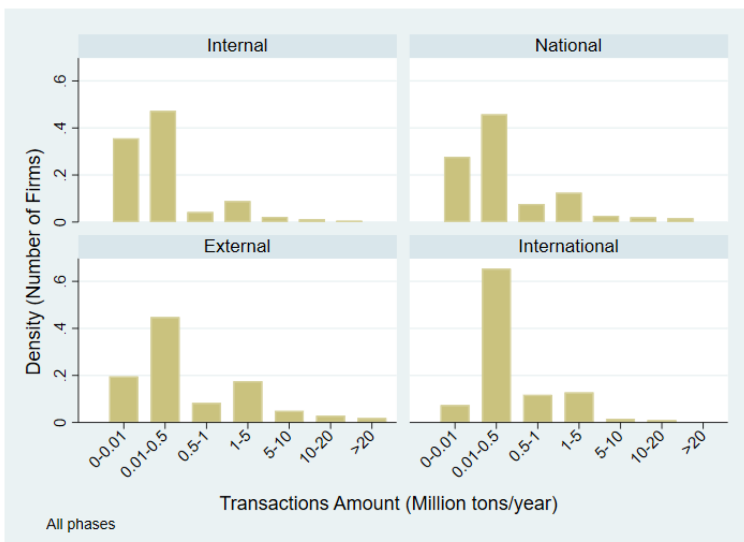


(c) International

Figure 2.3.: Purchases by Months and Type



(a) Quantity



(b) Density

Figure 2.4.: Transactions Amount by Type

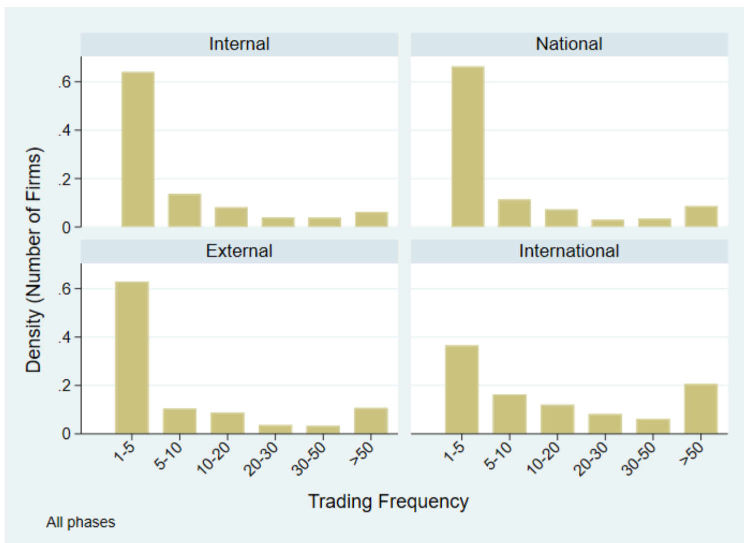


Figure 2.5.: Trading Frequency by Type

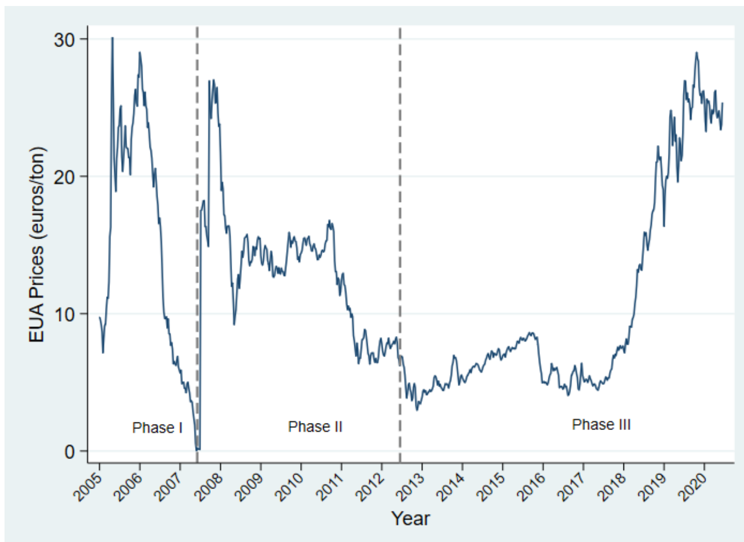


Figure 2.6.: EUA Prices

3. PRODUCTIVITY AND EMISSION TRADING BEHAVIORS: FIRM-LEVEL EVIDENCE FROM THE EU ETS

Yifei Xu, Purdue University
Pengfei Liu, University of Rhode Island

3.1 Introduction

The cap and trade system is the most common approach to regulating emissions such as carbon dioxide (CO_2) and serves as a useful instrument for climate change policy. The cap and trade system has received a lot of attention from both policy makers and researchers.[1] The EU ETS is the largest carbon cap and trade scheme in place. Recently, the EU ETS started to implement an auction approach in the European Commission. Similar auction mechanisms are also playing a more prominent role in other emerging regional emissions trading schemes in places like California (Cullenward and Coghlan, 2016; Keohane et al., 2017). The development of the EU ETS provides firms more options to obtain and sell emission permits. During the current phase of the EU ETS, besides collecting free allowances from the government (endowment), firms bid for permits from the European Commission (initial market), trade with other firms (secondary market), or use the entitled offset credits from countries outside the EU (international market). More flexible system with many trading alternatives creates firms more complicated decision making process. On top

[1]For example, in the 1980s, U.S. President Ronald Reagan authorized the use of a cap and trade system to phase out leaded gasoline. In 1989, President George H. W. Bush proposed the use of a cap and trade system to cut sulfur dioxide emissions by half from coal-fired power plants and acid rain. In 2005, the U.S. Environmental Protection Agency (EPA) under President George W. Bush issued the Clean Air Interstate Rule, which aimed to achieve “the largest reduction in air pollution in more than a decade" using cap and trade.

of participation decision, firms also need to make trade market choice and determine the trading amount of each market to minimize the cost. This paper is intended to answer some crucial questions: What are firms' permit trade market choice and trading amount? What are the determinants behind their trading behaviors? Do some firms have advantage in competing in the international market? What policy implications would be like? A better understanding about the current more complicated emission trading system and corresponding firms' participation behaviors is critical for the future development of the EU ETS and carries important implications for the mechanism designs in other regional trading schemes. To the best of our knowledge, our research provides a first look at the determinants behind firms' participation and trading behaviors including international offset permits.

A large body of work evaluating the impact of the EU ETS focuses on the efficiency of the trading market. However, little is known regarding the motivations behind firms' participation in emission trading and factors driving firms' trading behaviors. In our paper, we first develop an analytical framework to provide a benchmark for firms' participation and trading behaviors. This framework models emission reduction and permit trade with heterogeneous firms, and predicts that a more productive firm shows a larger emission abatement. More importantly, our framework indicates that the relationship between productivity and the optimal trading amount is ambiguous and potentially influenced by the transaction cost and the information availability in different permit trade markets. Under the guidance of this framework, we quantitatively analyze firms' participation decisions and permit trading patterns. We acquire firm level permit transactions data merged with detailed firm characteristics information. In contrast with other studies, we consider every aspect of the permit trade market, including the initial, secondary, and international markets. We estimate firms' total factor productivity (TFP) to represent firm-specific factors. In addition, we observe and investigate firms' profit in different trading markets. Our empirical results uncover the following trading behaviors in relation to firms' characteristics.

First, according to the data patterns, there are sizable regulated firms who do not participate in any permit trade market. For firms that actively participate in emission trading, participation choices vary across policy phases. Specifically, the firms participating in the permit trade market all trade in the secondary market in phase I (2005-2007). Starting from phase II (2008-2012), some firms, usually large and multinational firms, obtain permits internationally through their offset entitlements. Firms appear to participate in initial, secondary, as well as international permit markets starting from phase III (2013-2020). Our detailed trading patterns focus on the current phase III of the EU ETS, which has not yet been adequately analyzed in the literature.

Second, based on the empirical evidence, productive firms are more likely to participate in permit trading, especially in the international market. This finding is in line with the theory that a difference in marginal abatement cost (MAC) spurs participation in permit trading (Montgomery, 1972). The marginal abatement cost differs significantly among emitters because there are a wide variety of firms regulated in the EU ETS, providing incentives for trading in different markets. Note that the abatement cost of firms regulated by the EU ETS include permit transaction cost, administration cost, and search cost, which can be different depending on firms' market choices.[2] Those differences can lead to firms self-selecting into different trading markets.

Third, the results found when analyzing the supply side of the cap and trade market reveal that, given any permit trade market, productive firms are more likely to sell a larger number of permits. The demand side indicates that for firms purchasing permits in the initial market only or in the international market, productive firms are more likely to purchase a smaller number of permits. These findings suggest that productive firms have a greater capability to coordinate production, emission abatement, and allowance allocation, so that they are more flexible to shift the use

[2]For example, a much higher entry and transaction costs in the international permit trade market of the EU ETS is identified and estimated by Naegele (2018).

of their allocations across time, which creates opportunities for these firms to achieve compliance with the EU ETS without acquiring many permits though permit trading.

Fourth, productivity affects firm profit margins differently depending on the type of the permit trade market, indicating that less productive firms have disadvantages competing in the permit trading. These disadvantages are due to not only the fact that they do not participate in permit trading, but also by the choices they make when they do trade in the permits market. When permit markets are not classified by different types, studies find that the EU ETS is a compliance instrument rather than a profitable market-based instrument for regulating emitting firms (Martin et al., 2014). Our results fill the gap in previous literature where permit trade markets are not distinguished.

Fifth, our findings provide insights about the efficiency of the current trading system. Based on the fact that firms have an arbitrage opportunity to exchange cheaper offset permits by EUAs while remaining compliant with the EU ETS, we further discuss how cheaper international offset permits are more likely allocated to more productive firms or firms within the power sector. Put in another way, the current emission trading system with its international offset market introduces more potential arbitrage opportunities, which benefits more productive firms. In order to improve the efficiency of the system, our results suggest policy makers consider banning the international permits projects or setting sector- and group-specific offset limits like other countries.

The existing empirical literature investigating the EU ETS micro structure is sparse. Some micro studies have focused on permit trading behaviors by using the data of the European Union Transaction Log (EUTL). The trading data patterns suggest that firms' permit trading is passive and originally motivated by compliance obligations (Betz and Schmidt, 2016). Other studies reveal that compliance is not the only factor that affects the trading behavior of the regulated emitting firms. Some find that trading behavior is constrained by the transaction cost, especially for smaller firms (Jaraitė-Kažukauskė and Kažukauskas, 2015; Naegele, 2018). Our paper is in line with Zaklan (2013), who combines the firms' balance sheet information with trading transactions. Zaklan (2013) argues that a firm's trading volume is mostly impacted by the firm's permit endowment, defined as a market-specific factor, as well as its firm size, sector, and ownership structure, which are defined as firm-specific factors. Part of our results are consistent with Zaklan (2013), where the firm's characteristics such as firm age, ownership structure, and endowment position can determine whether a firm participates in the emission trading as well as what quantities a firm trades. However, Zaklan (2013) only looks at the binary of whether a firm chooses to trade or to not, while we investigate a more realistic situation by separating different permit trade markets in the analysis. In addition, we focus on the impact of a firm's total factor productivity on permit trading behaviors. Previous studies are mostly based on the first two phases of the EU ETS. Liu et al. (2017) find that firms' efforts have increased profits and saved costs during permit trading in the first two phases of the EU ETS. We further highlight firms' heterogeneous profit generation through participating in different types of trading markets during the three phases of the EU ETS.

There is an existing and growing literature on arbitrage opportunities in emission trading. Most studies focus on tradings only within the EU market. For instance, Chau et al. (2015) find that firms were actively seeking the arbitrage opportunities in the EU market through engaging in feed-back activities. An introduction of international offset permits brings more potential arbitrage opportunities, which negatively affects the transparency and efficiency of the trading system. However, Mansanet Bataller et al. (2010) suggest that although there is such an opportunity, it is limited in quantity due to the national offset limits. They also point out that arbitrage opportunities benefit mainly energy companies which possess large supplies of EUAs. Their analysis is based on a simulation model that does not, however, observe the real trade. Our study provides more empirical evidence on market inefficiency due to its examination of the linkage of international offset market. Consistent with Mansanet Bataller et al. (2010), we find that there is a potential arbitrage opportunity which benefits a group of firms: power firms, government-owned, and more productive firms.

The remainder of the paper is structured as follows. Section 2 documents the possible barriers of entry to the EU and international markets. Section 3 describes three sources of the data and analyzes the key data patterns. Section 4 draws out an empirical design and obtains the values of production parameters and productivity. Section 5 presents the results and provides discussions for policy implications. Section 6 includes additional robustness checks, and Section 7 offers a conclusion.

3.2 Discussion of Entry and Transaction Costs

The EU ETS is linked to the international offset market of the Kyoto Protocol. On aggregate, these additional foreign permits enlarge the cap for regulated firms within the EU and decrease their compliance costs since the offsets are cheaper than EUAs. However, as we observed and as many papers documented, more than 20% of regulated firms did not use any offsets during phase II (Naegele, 2018; Sato et al., 2016). As a result, offset usage becomes an unambiguous way to reduce compliance cost. Barriers to entering the international market and obtaining the offset permits could include higher entry and transaction costs. There is much evidence to support the idea of higher transaction costs in the international market. Many firms use costly trading services from consulting firms, exchange platforms or financial brokers. According to compliance account information, the permits transacted through financial and broker holding accounts are two times as large as the permits transacted through operating installations accounts. Furthermore, the transaction frequencies are four times larger in financial and broker holding accounts. This indicates that firms lack cost-free information. It takes an annual subscription fee of 2500 euros to set up a trading account at the ICE, the biggest exchange platform for the EU emission permits.[3]

[3]As reported from *www.theice.com/publicdocs/IFEU_Exchange_Clearing_Fees*

Many previous studies have also rationalized firms' trading behaviors by estimating firms' trading transaction costs (Heindl and Lutz, 2012; Jaraitė et al., 2010; Jaraitė-Kažukauskė and Kažukauskas, 2015; Löschel et al., 2011). These studies suggest that although there is no legal requirement or barrier to using offset permits from the EU Commission, there is supposed to be a fixed trading cost, both for general entry and each transaction. These costs include administrative costs due to mandatory actions, such as costs for monitoring, reporting and validating emissions, as well as the EU registry service charges. There are also trading or entry costs, such as information gathering, forecasting of allowance prices, finding trading partners, bargaining, contracting or managing price risk.

Based on this evidence of these additional costs, we believe trading costs lead to firms self-selecting out of the trading market with some small firms not seeing the benefit of entering the international offset market due to the upfront costs. We also expect larger firms to be more likely to obtain offset permits since international operating firms could decide to create offset permits in their own installations abroad, rather than purchasing the permits in the market place. Considering all of the aforementioned empirical evidence, our focus is on firms' heterogeneous behaviors and identifying which specific group of firms are purchasing offsets. Nevertheless, the question about the allocation of cheaper offset permits with the relevant arbitrage opportunities reflects the trading system efficiency.

3.3 Empirical Evidence

3.3.1 Data

In the empirical analysis, we combine three data sources. The first data source includes firm-level emission data from the World Carbon Market Database (WCMD), which contains detailed firm-level emission and allowance information aggregated from different carbon trading markets. The WCMD dataset contains regulated installations' emissions and free allowances at the individual firm level, which helps to identify firms regulated by the EU ETS. Firms that operate within at least one EU ETS regulated installation are identified as regulated firms. The WCMD data also provides firms' BvD (Bureau van Dijk) identifier that can be directly matched to the Bureau van Dijk Amadeus dataset. In addition, the WCMD data includes firms' detailed geographical information, such as region, city, street, building, zip code, and phone number.

The second data source is constructed based on the European Union Transaction Log (EUTL). The EUTL Transfer provides firms' detailed emission permit transactions data, such as account type, market type, amount of EUAs transacted, transaction time, and basic information on both parties in a transaction. The EUTL Transfer dataset contains dynamic data on the flow of permits, which are currently published with a delay of three years. The transactions of all regulated installations with an account were available for the period 2005-2016. At the time this study was performed, the most recent transactions with a complete calendar trading year was recorded in the end of December 2016. Therefore, I have excluded all transactions performed in 2017 as the compliance period for the year 2017 finished in April 2017.

The third data source is Amadeus data from the Bureau van Dijk database, which offers novel information on firms' production and financial statement. The Amadeus covers all firms in Europe with the inclusion of small private firms and presents each firm's production information, such as their sales, profits, employment, production costs, value added, export turnover, and detailed geographical information.

Based on the information contained in the three datasets, we are able to merge the above datasets using the common BvD identifier. A final merged dataset includes a panel dataset from 2005 to 2016 of 220 German firms. We choose German firms as a sample for our study due to several reasons: First, Germany takes the largest share of installations and emissions in the EU ETS with 25% followed by Poland with 11%. Second, Germany owns the largest amount of annual offset with 22% of annual cap of Germany. Last and the most important, there is no sector-specific offset limit in Germany, so that we are able to investigate offset trading in a fair environment.

For instance, Italy puts an 11%, 13.2%, 7.2%, and 5% offset limits on electricity, refineries, other industry sectors, and other combustion sectors, respectively.[4]

3.3.2 Permit Trading Patterns

We first summarize the general trading patterns in both purchases and sales, differentiated by market types. Firms are respectively allocated an endowment of 136, 1162, and 316 million tons of EUAs for phase I, phase II, and phase III in our sample. Accounts controlled by the firms in our sample acquired EUAs for a total of 362 million tons of CO_2 during the three phases and disposed of EUAs for 881 million tons of CO_2 over the same period. For convenience, we denote the initial market only as market type 1, the secondary market only as market type 2, the initial and secondary market mixed as market type 3, and any international market involved as market type 4.

Based on Table 3.1, there was an average increase in the number of emission permits traded from phase I to phase III. The majority of firms have traded through the secondary market in the first two phases. In phase III, the majority of firms trade through both initial and secondary markets. The average permit trading amount for firms that participated in the initial market is usually larger. On the demand side, Panel (a) in Table 3.1, firms participating in permit trading in phase I involve only the secondary market, where during years 2005 to 2007, they purchased only from other firms within the EU. There are some international permit purchases during phase II, and the amount increases in phase III. Different from the first two phases, there is a sizable number of permits purchases through the initial market in phase III. The permit demand in the secondary and international market has grown significantly in phase III.

As recorded in Panel (b) of Table 3.1, similar trading patterns are observed on the supply side. Firms sell permits through only the secondary market in phase I.

[4]UK, Spain, Denmark, Ireland, and Finland have sector-specific offset limits

The permit supply in the secondary market has grown significantly in phase II and III. However, a few firms sell permits to both initial and secondary markets starting from phase II. In addition, the regulated firms are not selling permits to firms outside the EU, although they could have bought permits from them.

We also consider the trading patterns in relation to firms' EUA position. We define a firm is *Long* when its allocation exceeds the verified emissions and *Short* when a firm's allocation does not exceed its verified emissions in the respective compliance year. We notice that the number of *Short* firms increases dramatically in phase III. Furthermore, *Long* firms appear to have realized their profit opportunities from selling EUAs more through the secondary market, while the *Short* firms tend to purchase permits more for compliance. Thus, firms' EUA endowment allocation appears to be related to involvement in permit trading.

3.3.3 Firm Characteristics

Table 3.2 summarizes the characteristics of the German firms which participated in permit trading during the regulated period. Table 3.2 (a) includes a sub-sample of firms that purchase EUAs and Table 3.2 (b) reports sub-sample of firms which sell EUAs. We observe that the sample is skewed towards large and more profitable firms receiving a substantial EUA endowment. Firms that purchase a positive number of permits have an average revenue of 4.0 billion Euros, receive an average allocation of about 0.2 million EUAs, and employ more than 5900 employees on average. On the supply side, the mean firm has a revenue of 4.4 billion Euros, receives an allocation of about 0.3 million EUAs, and has 4557 employees. Furthermore, on average, firms are slightly short on EUAs. The average firm on the supply side turns out to be more carbon-intensive with about twice as large of an endowment shortage than the mean firm that demands the permit, suggesting that the endowment position is not the only factor influencing firms' trading behaviors.[5] In addition, we collected firm

[5]There is a 24.7% endowment shortage in the mean firm on the demand side and a 52.6% endowment shortage in the mean firm on the supply side.

ownership information with 60% of the firms in our sample are government-owned companies, while 23% are family-owned companies. A half of the firms are classified as belonging to the combustion category by the EUTL, with the remainder having its main ETS related activity in the industrial sector.[6]

Table 3.3 summarizes the profit margin by market type. Overall, the average gross profit and the profit margin are higher for actively trading firms. Among actively trading firms, both the average gross profit and profit margin are higher for firms that purchase permits internationally on the demand side. On the supply side, firms selling permits through both initial and secondary markets have larger average gross profits and profit margins.

3.4 Empirical Methodology

3.4.1 Market Participation Choice

The regulated firms first make decisions regarding whether to trade and furthermore in which permit trade market to participate. Specifically, a firm's possible market choice includes no trading (market type=0), initial market trading only (market type=1), secondary market trading only (market type=2), both initial and secondary market trading (market type=3), and international market trading (market type=4).[7] The above decision process can be modeled through a discrete choice model for each firm i. We use a standard multinomial logit model to analyze individual compensation preferences. Consistent with the random utility framework (McFadden, 1973; Hanemann, 1984), we assume that the firm i maximizes utility (in our context, the expected profit) from choosing the permit trade market type j:

$$U_{ij} = V_{ij}(X_{ij}) + \epsilon_{ij}, j = 0, 1, 2, 3, 4. \tag{3.1}$$

[6] The details of activity and sector are listed in Table B.8.

[7] Market type 4 represents any firm who trades a positive amount of the international permits; any categorical market types are exclusive; and they capture a complete permit trade market.

The utility U_{ij} consists of an econometrically measurable, deterministic component, V_{ij}, and a random component, ϵ_{ij}, which is unobservable and assumed to follow an independent and identical extreme value type I distribution. The measurable component V_{ij} depends on a set of firm-specific and market-specific characteristics, denoted by X_{ij}. The regression model is then specified as follow.

For any firm i in market j at year t,

$$V_{ijt} = \beta_{0,j} ASC_i + \beta_{1,j} Productivity_{ijt} + \beta_{2,j} EndowmentPosition_{ijt} + \beta_{3,j} Phase_i, \quad (3.2)$$

where the ASC is the alternative specific constant. $Productivity$ is the estimated productivity measure. Firm productivity is measured by total factor productivity (TFP). We apply Levinsohn and Petrin (LP) to use the variation in intermediate input to proxy the unobservable productivity shocks, thus reducing the simultaneity problem (Levinsohn and Petrin, 2003). The estimated input coefficients and TFP statistics of the German sample are given in Table 3.4. $EndowmentPosition$ indicates a firm's EUA position based on the difference between its endowments and verified emissions. The EUA position is a dummy variable equaling 1 if a firm was *Long* on EUAs at the end of the respective period of obligation. $Phase$ reflects the market environment and the stage of the trading market. The subscript t is added to denote the year of transaction. We apply the maximum likelihood procedure to focus on testing the influence of productivity on market choice.

3.4.2 Permit Trading Amount

Conditional on the market participation decision, firms also choose the number of permits to trade. We use a regression model to identify factors that influence the permit trading amount.

For firm i that participated in market type j at year t,

$$y_{ijt} = \alpha_{0,j} + \alpha_{1,j} Productivity_{ijt} + \alpha_{2,j} EndowmentPosition_{ijt} + \alpha_{3,j} EndowmentStock_{ijt} + FE + \mu_{ijt}, \quad (3.3)$$

where $FE \equiv \eta_r + \eta_d + \eta_f + \eta_y$.

The dependent variable, y, is the logarithm of the amount of emission permits traded. The explanatory variables *Productivity* and *EndowmentPosition* have the same definitions as in equation (3.2). *EndowmentStock* is the value of endowment stock, constructed by average EUA market price (p) each year times firm's quantity of endowment at that year. Using the average EUA market prices should give a good approximation of the average gains under the assumption that permits allocated in a year are most likely to have been sold or bought within the same year. The η_r, η_d, η_f, and η_y control for the region, industry, firm, and year fixed effects, respectively.

3.5 Results and Discussion

3.5.1 Market Participation Choice

A firm first decides on whether to trade or in which permit trade market to participate. Conditional on the participation choice, the firm then decides the amount it will trade. We first present results on firms' market participation choices. In the analysis, we use no trading (market type=0) as the baseline category.

Firm Purchases We first consider the demand side of a firm's participation choice. Our estimation reveals that firm characteristics significantly predict participation in EUA permit trading on the buyer side. The estimated coefficients are reported in Panel A of Table 3.5 by the relative log odds with baseline market type 0 (no trading). The results indicate a 1% increase in productivity leads to a 25% increase in the relative probability of trading in the secondary market rather than not trading, and a 44% increase in the relative probability of trading in both initial and secondary markets over not trading. The relative probability of trading in the international market rather than not trading is also doubled as a result of a 1% increase in productivity.[8] There is a negative but insignificant effect of productivity on initial market only permits trading with a 1% increase in productivity resulting in a 13% decrease

[8] The relative probability of trading in the international market rather than not trading is 2.04

in the relative probability. In short, firm productivity is associated with an increase in the relative probability of participating in permit trading over not trading, but also a much larger increase in the relative probability of trading in the international market over not trading.

Our coefficient estimates suggest the importance of firms' heterogeneity on permit trade participation and market choice. For example, Zaklan (2013) shows that firm size, measured by the log value of turnover, is positively and significantly related to the probability of engaging in EUA purchases. Their estimates indicate that a 1% increase in turnover leads to a 4.5% increase in the probability of participating. Consistent with the literature, our results show that firm characteristics significantly predict participation in firm EUA trading on the buyer side. In addition, we also provide new information about firms' decisions among different trade markets. More productive firms are more likely not only to participate in permit trading but also are more likely to obtain permits from the international offset market. This finding reveals that the cheaper international offset permits are more likely to be allocated to more productive firms.

We use a dummy variable endowment position to represent the permit endowment status of a firm in a specific year. In our analysis, endowment position equals 1 if the firm is *Long* and 0 if the firm is *Short* in the corresponding compliance year. With the same productivity and phase, the relative probability of participating in trading rather than not trading is 24%-51% lower for *Long* firms than for *Short* firms depending on firms' market choices. Zaklan (2013) also provides strong evidence that firms which were *Long* on EUAs were significantly less likely to engage in EUA purchases in phase I with the probability of participating in trading at 32.3% and 45.4% lower for *Long* firms in 2005 and 2006 respectively. We look into firms' market choices by focusing on the participation in the international offset market. We find that the relative probability of trading in the international market rather than not trading is 51% lower for *Long* firms than for *Short* firms.

In addition, we also consider the changes across phases. Thus, the relative probability of trading only in the secondary market rather than not trading is 76% lower in phase II than phase I with the same productivity and endowment position. This relative probability drops to 94% lower in phase III than in phase I. This result is in accordance with the policy changes staring in phase II: firms are allowed to use international offsets from the international market and to trade in the initial market. Because firms have more options on purchasing permits, the probability of being in the secondary market only in phase II and phase III decreases. However, since we have only a limited number for certain types of market trading observations, as shown in Table 3.1, the coefficient estimates are not precise for some phase dummies. We are able to draw conclusions for only the changes in the trading pattern for firms participating in the secondary market across different trading phases.

Firm Sales We next consider the supply side of the EU ETS. Analogous to our results on the demand side, we find that productive firms are more likely to participate in permit selling through only the secondary market or through both initial and secondary markets. According to Panel A in Table 3.6, a 1% increase in productivity is associated with a 26% increase in the relative probability of trading in secondary market compared with not trading and a 32% increase in the relative probability of trading in both the initial and secondary markets compared with not trading. There are no selling permits to the international market. These findings are different from the conclusion in Zaklan (2013) that productivity has no effect on trade participation choice on the supply side.

There are several reasons why our results suggest differently. First, the patterns in permit trade are demonstrated only in the first phase of the EU ETS in Zaklan (2013). We cover all three phases and focus on phase III, so the different scopes of the studies potentially drive the main variations. The first phase especially works as a pilot phase by only allowing secondary market trading. We believe that phase II and III can reflect the impact of the EU ETS on the permit trading patterns of enterprises more realistically and accurately. In addition, we use different measures of productivity. To be specific, TFP is a more concise measure of firm productivity than proxies, such as a firm's turnover, assets, or employment. Furthermore, Zaklan (2013) only includes the transactions among firms by investigating inter-firm trade and intra-firm transfer. We consider other types of trading markets and exclude the internal transfers within a firm. Our results solve the puzzle of Zaklan (2013), where the transaction cost considerations play an opposite role on the demand and supply sides of the EUA trade. While we expect similar roles on both sides, productive firms on the supply side are more likely to participate in the EUA trade.

We also perceive that the position of the EUA endowment available for trading positively and significantly predicts the likelihood of engaging in the sale of EUAs. Specifically, the relative log odds of participating in the initial or secondary market of selling permits compared with not involving permits trading will increase by 0.25-0.60 when a firm is in a *Long* endowment position rather than a *Short* endowment position. This indicates that being long on the endowment increases the probability of selling EUAs by around 28%-82%. This result is consistent with the findings of Zaklan (2013), who discovers the effect of a strongly significant endowment position on firms' participation: being long on endowment increased the probability to sell EUAs by some 27%-33%, both in the years 2005 and 2006. Our data shows that the relative probability of selling in the secondary market compared with not trading decreases by 98% in the phase III trading period from the data found in the phase I trading period of the EU ETS. There is no significant difference in this pattern between phase II and phase I on the supply side. This result suggests that the policy stage changes may affect the demand and supply sides differently. The allowance of offset usage may affect the demand side more while the openness of the initial market may impact the supply side more.

3.5.2 Permit Trading Amount

Conditional on market choice, we next turn to a firm's decision of what quantities to trade in permit trading by investigating the relationship between some factors and trade quantities. Specifically, we look at market-specific factors such as endowment position and value of endowment stock, as well as the firm-specific factor represented by productivity.

Firm Purchases As shown in Table 3.5 Panel B, our estimates indicate that more productive firms participating in both initial and secondary markets tend to purchase more permits. A 1% increase in productivity can result in a 3.4% increase in purchases. More productive firms participating in either the initial market only or the international market tend to purchase fewer permits, with a 1% increase in productivity decreasing its amount of purchase by 1% and 2.7% accordingly. Productivity does not have a significant effect on the amount of purchase for firms trading only in the secondary market. We also find that the value of endowment stock has a significant effect on the amount decision, with a smaller initial value of EUA stock leading to larger purchases. Finally, we find that a firm's endowment position effect is significant for firms that trade in both initial and secondary markets, with firms that were *Long* on permit ex post buying fewer permits, ceteris paribus.

Firm Sales We then consider the amount decision on the supply side. As presented in Panel B of Table 3.6, the more productive firms participating in any permit trade market all tend to sell more permits, with a 1% increase in productivity increasing a firm's amount of sales by 0.5% in the initial market only, 0.9% in the secondary market only, and 0.4% in both the initial and secondary markets. Different from the result of buyers, the effect of the value of endowment stock on trading amount is insignificant in many cases for sellers. This indicates that instead of selling their permits based on large endowment stock, some firms who have extra permits may see larger benefit in banking unused permits for future use.

3.5.3 Main Results Discussion

We summarize the main results and discuss their policy implications. More productive firms are more likely to participate in permits trading and to purchase the permits in the international market. At the same time, more productive firms are more likely to sell permits in the secondary market to firms within the EU. This trend suggests an arbitrage opportunity existing for more productive firms. They could obtain cheaper permits in the international market and then sell the permits to firms in the EU with a higher EUA market price. Conditional on firms' market choice, the permit trading amount correlates with a firm's productivity and endowment value. There are some previous studies looking at arbitrage opportunities in the emission trading market only within the EU, finding that in that dataset, firms were actively seeking arbitrage opportunities by engaging with feed-back activities. When there is an international offset market introduced with more potential arbitrage opportunities, it is hard to believe firms won't take it. Our results suggest there is an arbitrage opportunity here and that this opportunity benefits more productive firms. Our findings are in line with a reform of the policy in phase IV based on Market Stability Reserve (MSR). It states that there were some unusual levels of profits for this types of permits, and that we need to increase the overall transparency and effectiveness of the EU ETS in phase IV (2020-2030).

We further explain why productive firms have the advantage in the international market by discussing the possible barriers to enter the international offset market. Transaction costs pose a barrier to smaller firms who want to exercise the opportunity to use offsets for compliance, suggesting the importance of internal capacity at the company level. This also suggests that smaller companies may be more constrained in terms of managerial availability and manpower, the ability to collect the necessary information and make an informed decision about whether or not they should enter the international trading market (Buckley, 1989). Trotignon (2012) looks at offseting within the EU ETS in 2008 and 2009 and finds that factors such as transaction costs particularly affect small installations. We might also consider how the impact of these transaction costs lowers barriers for companies with international linkages in offset countries. Indeed, a number of studies point to the importance of having international subsidiaries. Michaelowa and Jotzo (2005) argue that transaction costs in CDM projects can account for a significant share of the total cost of the investment but can be eliminated in the case of investment in their own subsidiaries. Thus, companies with an international presence have better opportunities to invest in CDM projects. Sato et al. (2016) find evidence that firms with subsidiaries in CDM and JI countries are likely to have a much greater capability to engage in these projects than those without. These studies have not examined the important distinction between the motivations of those engaged in directly investing in primary offset permits and those purchasing in the secondary market. Our paper focuses on the demand side of purchasing the offset permits. In addition, prior works mostly use survey data to show that a number of firm level characteristics may influence offset usage. We use compliance data and consider both firm and market level characteristics that may influence offset purchasing.

3.5.4 Profit Margin

To support the evidence for this arbitrary opportunity, we further examine firms' profits through permit trading. Table 3.7 demonstrates the relationship between a firm's profit margin and productivity. We include an interaction term of productivity and market type to capture the heterogeneous effect of productivity on a firm's profit margin when the firm participates in different types of permit trade markets.

Firm Purchases On the demand side, we find that for firms without permit trading, the effect of productivity is 3.765. Therefore, more productive firms would be expected to have larger profit margins than less productive firms with a one-unit productivity increase resulting in a 3.765% increase in profit margin. For firms in the secondary permit trade market, however, the effect of productivity is 6.813. Therefore, for two firms in the secondary permit trading market, the more productive firm would be expected to have a larger profit margin than a less productive firm, with a one-unit productivity increase resulting in a 6.813% increase in profit margin. Similarly, a one-unit productivity increase results in a 5.692% and 12.719% increase in profit margin for firms in both the initial and secondary markets and the international permit trade market, respectively. Because of the interaction, the effect of productivity is different based on permit trade market type. As a result, more productive firms gain more profit through participating in permit trading, especially through involving the secondary and international permit trade markets.

Firm Sales We observe a different pattern of profit margin on the supply side. The results show that more productive firms obtain less profit through participating in permit trading, especially when involving the secondary permit trade market. Specifically, for firms not engaged in permit trading, the effect of productivity is 6.997, which is about twice as large as the effect for purchasing firms. Therefore, for two firms not participating in the permit trade market, more productive firms would be expected to have larger profit margins than a less productive firm, with a one-unit productivity increase resulting in 6.997% increase in profit margin. For firms in the secondary permit trade market, however, the effect of productivity is 5.195. Thus for two firms in the secondary permit trade market, the more productive firm would be expected to have larger profit margins than a less productive firm with a one-unit productivity increase resulting in 5.195% increase in profit margin. Similarly, a one-unit productivity increase results in 6.614% and 6.8% increase in profit margin for firms in the initial market only, and both the initial and secondary markets accordingly. Additionally, the interaction term of productivity and phase captures the effect of productivity on profit margins across policy periods. It reveals that more productive firms generate less profit in phase II when compared to phase I, and the effect becomes even more prevalent in phase III.

3.6 Robustness Check

In this section, we provide the results using alternative model estimations and specifications as a robustness test. Table 3.8 presents the results using different multinomial logit models. Following Pforr (2014), the multinomial logit model with fixed effects takes into account possible unobserved heterogeneity at the firm level with respect to the characteristics for a specific party. For the pooled multinomial logit model, panel-robust standard errors are used to control possible correlations across waves. In these two alternative models, heterogeneity is captured in time-invariant variables: sector, firm age, and firm type.

The outputs in Table 3.8 are consistent across the three models. We focus on the effect of productivity on permit trade market choice. As mentioned before, we prefer the multinomial logit model with fixed effects. The coefficient of productivity shows the logarithm of the relative-risk ratios for a one-unit change in the corresponding variable. With an increase in the productivity of a firm by one unit ceteris paribus, the logarithm of the probability to participate in the secondary permit trade market divided by the probability not to participate in the permit trade market increases by 0.258. Equivalently, when productivity increases by one unit, the odds of participating in the secondary permit trade market versus not participating in the permit trade market increase by a factor of 1.29, or 29.4%. Similarly, with each unit increase in productivity, the odds of participating in both the initial and secondary permit trade markets versus not participating in the permit trade market increase by 38.1%, and the odds of participating in the international permit trading market versus not participating in the permit trade market increase by 128.4%. The results indicate that if the productivity increases by one unit, the odds to participate in both the initial and secondary permit trade markets versus participating in the secondary permit trade market only increase by a factor of 1.067 or 6.7%. There is no significant influence of productivity on initial market participation relative to no participation in the permit trading. In addition, the endowment status plays a role in permit trading market choice. Results show that firms short of permit endowments are more likely to purchase permits through permit trading. We also find that electricity power firms are more likely to participate in the permit trade market than any other manufacturing firms. The power sector is the most emission intensive among all regulated sectors. On average, power firms are short of permit endowments, and no permit endowments are granted to the power sector starting from phase III. The power sector characteristics, as well as tighter policy stringency compared to other industries, makes power firms actively purchase permits by participating in the permit trade market.

For robustness testing the trading amount decision, we perform additional regressions excluding TFP but considering other potential driver-variables of permit trade. Following Zaklan (2013), we adopt firm characteristics variables which imply firm productivity. The main results are broadly similar in terms of coefficient size and significance. As demonstrated in Table 3.9, larger firms, measured by size of employment, purchase more permits, suggesting that an increase in the log value of the employment by 1% increases purchases by between 0.28% and 0.56%, depending on the regulation phase. We also find a significant impact of firm ownership structure, with family-owned companies acquiring fewer permits. Additionally, we discover that firm age has a small but significantly positive effect on the amount of permit purchases and firms in power sector buy significantly more permits. Thus, we confirm that the amount decision appears to be dominated by the firm-specific factors.

3.7 Conclusion

Regional carbon trade market is proposed as an effective way of combating climate change. A cap and trade framework serves as a useful instrument in trade market design. The EU ETS is the largest carbon credit trading market based on a cap and trade framework. Most previous research focuses on the efficiency of the trading market. However, little is known regarding firms' participation and trading behaviors. Our research provides a first look at the determinants behind firms' participation and trading behaviors based on a comprehensive permit transaction dataset linked with firm's characteristics in Germany.

We focus on how the regulated firms participate and trade emission permits in different trading markets under the EU ETS. First, we overview detailed descriptive permit trading patterns during the three phases of the EU ETS including three different types of trade markets, which, to the best of our knowledge, has not been analyzed in detail. Second, we provide an analytical framework to understand the firms' trading behaviors. We allow firm level heterogeneity and then derive the optimal abatement and trading amount depending on the firm's characteristics. Based on our assumption, we find that productive firms are likely to abate more while the optimal trading amount is uncertain. We then link the modeling implications to the EU ETS context and discuss the implications of transaction costs and information availability on firms' trading choices. In the end, while focusing our attention on both the demand and supply sides of the permit trading, we test predictions regarding the firm level determinants of the permit trade from the general trade literature, such as the greater propensity for participation in trade based on productivity.

Our empirical results show that the trading behaviors are driven by compliance obligation. Firms are most likely to purchase permits when they need to avoid financial penalties, particularly at the end of the compliance cycle. Additionally, the results indicate that the trading behaviors of the firms are found to be affected by their productivity, industry, ownership structure, and permit endowment. We observe that more productive firms are more likely to participate in permit trading and purchase permits in the secondary and international markets. More productive firms participating in the both initial and secondary markets also tend to purchase more permits, while productive firms participating in either the initial market only or the international market tend to purchase fewer permits. Firms in the power sector and government-owned firms tend to acquire larger permits. Firms in a *Short* endowment position are more likely to participate in permits trading. A significant effect of the value of EUA endowment on trading amounts is also identified, with a smaller value of endowment stock leading to larger purchases.

We provide some insights about our findings on firms permit trading behaviors. In line with the current stage of the EU ETS, we have taken a complete portfolio of permit trade markets as the consideration set. Firms face different transaction, monitoring, reporting and verification of emissions (MRV) costs in each permit trade market. The firm's diverse ability to obtain the "best" resources results in different trading behaviors. As a result, the variation of the costs due to their trade choice may lead to a loss of competitiveness for less productive firms. Therefore, the design of the policies is essential to balance the loss of competitiveness, e.g. exemptions. Moreover, our findings suggest that different possible permit trade markets offer different trading environments and attributes, which more reflect firms' capabilities in searching, monitoring or transaction cost saving. These productive firms with better capabilities occupy the "best" resources, thus leading less productive firms have disadvantages competing in the permit trade market. Productive firms obtain cheaper offsets from the international market and sell to EU firms with a higher EUA price. Due to this arbitrage opportunity, they will not be willing to abate or invest in green innovation. However, these large and productive firms should be the target firms who need the abatement and innovation the most.

Overall, a more unified and standardized permit trading platform needs to be considered, especially for some registries who do not have a sector-specific offset limit. In order to improve the efficiency of the current trading system, Germany may learn from other registries to set up sector- or group-specific offset limits.[9] More research is needed to fully rationalize firms' trading strategies in the complicated permit trade process and the policy implications for system efficiency. There are still many questions worth pursing related to firms' trading behaviors, including what are the transaction costs and search costs in each permit trade market? How much quantitatively do these costs affect trading behaviors? Could there be optimal policies? And

[9]Italy, UK, Spain, Denmark, Ireland and Finland have sector-specific offset limits.

how might the trading behavior vary in removing international market vs. expanding international market? We leave these questions for future research.

Table 3.1.: EUA Trading Patterns, by Firm Allowance Position, Market Type and Phase

(a) German Firms Purchases

				Market Type			
		Firms	Surplus	1	2	3	4
Phase I	Long	207	26051	0	190351	0	0
	Short	77	-47051	0	28428	0	0
Phase II	Long	215	236739	0	84352	0	356522
	Short	110	-151142	0	205152	0	199539
Phase III	Long	80	256772	27854	21091	238398	17729
	Short	245	-267153	90195	70030	1442259	849376

(b) German Firms Sales

				Market Type			
		Firms	Surplus	1	2	3	4
Phase I	Long	181	38898	0	109125	0	0
	Short	52	-113306	0	94631	0	0
Phase II	Long	299	387174	0	623980	74624	0
	Short	114	-3070691	0	1546809	5000	0
Phase III	Long	158	124192	39139	80522	2838700	0
	Short	430	-1570424	207761	29091	1813760	0

Notes: Long indicates that the firm's allocation exceeds its verified emissions in the respective compliance year. Short indicates that the firm's allocation does not exceed its verified emissions in the respective compliance year. Surplus is a firm's permit purchases or sales are in average with unit of tCO_2e

Table 3.2.: Summary Statistics, 2005-2016

(a) German Firms Purchases

Variable	Obs	Mean	Std. Dev	Min	Max
Endowment (EUAs) (tCO_2e)	5031	155739	616210	0	878058
Verified Emissions (tCO_2e)	5031	194280	627433	0	7679643
Revenue (Thousand Euro)	4614	4011361	12000000	0.416	108000000
Employment Cost (Thousand Euro)	4461	539681	1595376	0.792	12800000
Working Capital (Thousand Euro)	5178	243046	793007	-367000	5900000
Material Cost (Thousand Euro)	2995	3209261	9467919	0.409	71500000
Number of Employees	4950	5955	18680	1	152995
Return on Assets (in Percent)	4712	4.23	7.76	-66.10	93.67

(b) German Firms Sales

Variable	Obs	Mean	Std.Dev	Min	Max
Endowment (EUAs)(tCO_2e)	5167	312450	1962717	0	55400000
Verified Emissions (tCO_2e)	5167	476896	3664543	0	91600000
Revenue (Thousand Euro)	3875	4363428	11500000	0.420	108000000
Employment Cost (Thousand Euro)	3735	418769	1517632	0.790	12800000
Working Capital (Thousand Euro)	4404	165260	646883	-367000	5900000
Material Cost (Thousand Euro)	2489	2730934	9216816	0.410	71500000
Number of Employees	4203	4557	17765	1	152995
Return on Assets (in Percent)	3959	4.32	8.06	-66.11	93.67

Table 3.3.: Firm Profit by Market Type

	Firm Purchases					Firm Sales				
	Obs	Mean	Std.Dev	Min	Max	Obs	Mean	Std.Dev	Min	Max
Market Type: 0										
Gross profit (million euro)	88	1710	3310	-3.51	14400	147	2308.02	3252.07	.01	14400
Profit margin (%)	1053	8.05	22.93	-98.46	97.86	1111	11.13	25.27	-98.46	97.86
Market Type: 1										
Gross profit (million euro)	5	1350	2270	21	5380	27	3523.67	3414.13	25.70	11600
Profit margin (%)	67	5.77	15.75	-61.84	51.47	153	6.03	25.27	-61.84	91.14
Market Type: 2										
Gross profit (million euro)	45	2540	3730	4.99	14600	214	3209.04	3520.73	-3.51	14600
Profit margin (%)	394	8.11	21.63	-97.67	93.44	1089	11.12	24.60	-97.67	93.44
Market Type: 3										
Gross profit (million euro)	22	3810	5580	17.8	18300	139	4010.12	4398.12	16.26	18300
Profit margin (%)	137	9.11	24.73	-98.99	98.99	618	11.36	25.62	-98.99	98.99
Market Type: 4										
Gross profit (million euro)	8	6320	5150	86.3	15500					
Profit margin (%)	40	11.22	24.45	-68.69	82.08					

Table 3.4.: Comparison of OLS, FE, and LP estimators of all German firms

Parameter	OLS	FE	LP
α_{labor}	0.2572***	0.1862***	0.2048***
	(0.0294)	(0.0410)	(0.0915)
$\alpha_{capital}$	0.2986***	0.0282*	0.1365***
	(0.0277)	(0.0181)	(0.0485)
$\alpha_{material}$	0.3540***	0.3987***	0.4082*
	(0.0221)	(0.0529)	(0.2836)
TFP (*mean*)	2.7891	5.4665	4.1958
	(0.6113)	(0.8571)	(0.6950)

Dependent variable is a log of revenue

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 3.5.: Determinants of Firm EUA Purchases

(a) Panel A: Permit Trading Market Choice

	(1) Productivity (LP)				(2) Productivity (FE)				(3) Productivity (OLS)			
Market Type	1	2	3	4	1	2	3	4	1	2	3	4
ln(Productivity)	-0.142	0.225**	0.366**	0.711***	-0.164	0.199**	0.286**	0.680***	0.0108	0.248**	0.453**	0.629**
	(0.230)	(0.110)	(0.176)	(0.241)	(0.183)	(0.0902)	(0.141)	(0.207)	(0.270)	(0.123)	(0.203)	(0.249)
Endowment Position: Long	-0.422	-0.295*	-0.274	-0.705*	-0.430	-0.295*	-0.275	-0.719*	-0.404	-0.293	-0.268	-0.696
	(0.299)	(0.178)	(0.249)	(0.427)	(0.299)	(0.178)	(0.249)	(0.428)	(0.299)	(0.178)	(0.249)	(0.425)
Phase II	-0.0258	-1.437***	-0.0494	17.90	-0.0133	-1.452***	-0.0685	17.83	-0.0329	-1.416***	-0.0115	17.98
	(4255.7)	(0.219)	(3426.5)	(5492.9)	(4244.1)	(0.220)	(3429.6)	(5515.4)	(4275.7)	(0.219)	(3423.0)	(5505.7)
Phase III	18.63	-2.852***	18.64	16.63	18.65	-2.875***	18.61	16.51	18.63	-2.818***	18.70	16.75
	(4048.7)	(0.288)	(3260.6)	(5492.9)	(4037.5)	(0.289)	(3263.5)	(5515.4)	(4068.1)	(0.287)	(3257.4)	(5505.7)
N	1143				1143				1143			
R^2	0.185				0.186				0.184			
BaseOutcome	0				0				0			

(b) Panel B: Permit Trading Amount

	(1) Productivity (LP)				(2) Productivity (FE)				(3) Productivity (OLS)			
Market Type	1	2	3	4	1	2	3	4	1	2	3	4
ln(Productivity)	-0.973***	-0.147	3.396***	-2.691*	-0.895***	0.988	2.437***	-2.717***	-0.713	-1.297**	3.389*	0.0431
	(0.170)	(1.239)	(1.008)	(0.991)	(0.0418)	(0.684)	(0.557)	(0.191)	(0.424)	(0.624)	(1.930)	(1.519)
Endowment Position: Long	0.0518	-0.492	-3.573**	0.527*	0.0732***	-0.401	-3.610**	0.0151	0.0156	-0.480*	-2.706	0.418
	(0.0306)	(0.294)	(1.654)	(0.193)	(0.0230)	(0.298)	(1.718)	(0.102)	(0.0375)	(0.271)	(1.727)	(0.422)
ln(Value of Endowment Stock)	-57.30***	8.872	-33.44***	-619.5***	-58.81***	9.985*	-27.29***	-61.52	-59.04***	3.833	-40.89***	-1071.1***
	(0.828)	(5.840)	(9.141)	(121.0)	(0.440)	(5.097)	(7.939)	(91.24)	(1.821)	(5.165)	(13.47)	(204.6)
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	No	No	No	No	No	No	No	No	No	No	No	No
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	28	214	55	14	28	214	55	14	28	214	55	14
R^2	0.994	0.686	0.226	0.910	0.997	0.703	0.241	0.989	0.983	0.712	0.143	0.829

Notes: Firms trade decision including permit trading market choice (panel A) and permit trading amount (panel B) are expressed at all German EUA-purchase firms in the sample. Panel A reports the estimation results of multinomial logit model relative to non-trade firms in three different measures of productivity (1)-(3). More productive and short position firms are more likely to purchase permits from other firms and internationally. Panel B reports the associated purchase amount estimation results conditional on market choice. More productive firms are likely to purchase less through EU Commission but more from other firms. Firms have less endowment permits amount are purchasing more permits.

Table 3.6.: Determinants of Firm EUA Sales

(a) Panel A: Permit Trading Market Choice

	(1) Productivity (LP)			(2) Productivity (FE)			(3) Productivity (OLS)		
Market Type	1	2	3	1	2	3	1	2	3
ln(Productivity)	-0.0299	0.229***	0.277***	-0.0326	0.138***	0.166***	0.0401	0.167**	0.393***
	(0.106)	(0.0642)	(0.0727)	(0.0755)	(0.0447)	(0.0509)	(0.132)	(0.0725)	(0.0836)
Endowment Position: Long	0.326	0.250	0.253	0.451*	0.603***	0.508***	0.446*	0.589***	0.488***
	(0.256)	(0.156)	(0.188)	(0.235)	(0.119)	(0.165)	(0.235)	(0.119)	(0.166)
Phase II	0.178	0.251	13.62	0.105	0.0635	13.14	0.0871	0.104	13.17
	(2317.9)	(0.192)	(1193.3)	(1514.1)	(0.166)	(761.2)	(1514.7)	(0.165)	(756.7)
Phase III	18.55	-4.496***	18.35	17.87	-3.869***	17.79	17.85	-3.814***	17.84
	(2139.6)	(0.493)	(1193.3)	(1399.8)	(0.326)	(761.2)	(1400.1)	(0.325)	(756.7)
N	2387			2387			2387		
R^2	0.350			0.333			0.335		
BaseOutcome	0			0			0		

(b) Panel B: Permit Trading Amount

	(1) Productivity (LP)			(2) Productivity (FE)			(3) Productivity (OLS)		
Market Type	1	2	3	1	2	3	1	2	3
ln(Productivity)	0.462**	0.888**	0.308	0.425***	0.523***	0.367*	0.240	0.0358	0.416*
	(0.177)	(0.403)	(0.357)	(0.103)	(0.188)	(0.204)	(0.421)	(0.284)	(0.240)
Endowment Position: Long	0.482	-0.137	-0.867*	0.641*	0.131	-0.650	0.574	0.0759	-0.746*
	(0.445)	(0.184)	(0.464)	(0.363)	(0.191)	(0.415)	(0.431)	(0.190)	(0.412)
ln(Value of Endowment Stock)	-357.5**	41.99	-15.52	-367.0**	70.43	-20.31**	-372.5**	70.35	-20.62**
	(165.8)	(102.9)	(10.30)	(156.9)	(117.6)	(9.475)	(161.5)	(114.8)	(9.575)
Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	No	No	No	No	No	No	No	No	No
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	88	665	329	122	899	469	122	899	469
R^2	0.687	0.337	0.208	0.785	0.363	0.213	0.764	0.350	0.210

Notes: Firms trade decision including permit trading market choice (panel A) and permit trading amount (panel B) are expressed at all German EUA-sales firms in the sample. Panel A reports the estimation results of multinomial logit model relative to non-trade firms in three different measures of productivity (1)-(3). More productive and long position firms are more likely to sell permits to other firms. Panel B reports the associated sales amount estimation results conditional on market choice. More productive firms are likely to sell more to EU Commission and to other firms. Firms have less endowment permits amount are selling more permits.

Table 3.7.: Firm Profit Margin and Productivity

	(1) Firm Purchases			(2) Firm Sales		
	Productivity			Productivity		
	(LP)	(FE)	(OLS)	(LP)	(FE)	(OLS)
ln(Productivity)	3.765**	3.657***	2.478***	6.997***	4.376***	2.949**
	(1.519)	(1.348)	(1.593)	(1.146)	(1.141)	(1.800)
Market Type						
1	-0.834	2.133	-3.745	3.663	-26.58**	-19.98**
	(8.996)	(9.438)	(7.127)	(9.542)	(11.85)	(7.759)
2	-12.04**	-5.287	-11.97***	18.76**	-20.04**	-22.17***
	(4.980)	(5.168)	(3.802)	(7.415)	(7.987)	(5.596)
3	-6.519	-0.338	-9.498*	2.483	-33.65***	-20.15***
	(7.098)	(7.701)	(5.169)	(7.400)	(8.740)	(5.678)
4	-35.72***	-5.428	-39.58***			
	(10.04)	(10.90)	(6.781)			
Interaction (Productivity, Market Type)						
1	0.248	-0.316	1.334	-0.383	2.326**	4.804**
	(2.122)	(1.711)	(2.498)	(1.019)	(1.117)	(1.990)
2	3.048***	1.080	4.602***	-1.802**	1.734**	5.591***
	(1.176)	(0.935)	(1.342)	(0.799)	(0.748)	(1.454)
3	1.927*	0.349	3.995**	-0.197	2.820***	4.416***
	(1.616)	(1.339)	(1.760)	(0.775)	(0.805)	(1.428)
4	8.954***	1.689	14.76***			
	(2.199)	(1.823)	(2.197)			
Interaction (Productivity, Phase)						
Phase II	0.346	-0.374	0.885	-2.557**	-0.953	0.876
	(1.284)	(1.120)	(1.393)	(0.998)	(0.965)	(1.394)
Phase III	-0.263	-0.469	-1.218	-4.020***	-1.848	-1.141
	(1.539)	(1.307)	(1.727)	(1.207)	(1.171)	(1.970)
Endowment Position: Long	0.0187	-0.220	0.142	-0.750	-2.384***	-2.306***
	(0.667)	(0.681)	(0.656)	(0.587)	(0.716)	(0.710)
ln(Endowment Stock)	-2.383	-2.039	-1.879	-7.178	8.888	6.955
	(2.775)	(2.835)	(2.727)	(22.18)	(34.23)	(33.83)
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	880	880	880	1572	2224	2224
R^2	0.548	0.529	0.566	0.494	0.402	0.412

Notes: The relationship between firm profit margin and productivity are expressed at all German firms in the sample. (1) reports the estimation results of firms in demand side and (2) presents the estimation results of firms in supply side. More productive firms gain more profit through participating in permit trading, especially through involving the secondary and international permit trading markets.

Standard errors in parentheses

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 3.8.: Permit Trading Market Choice (Buyers)

	POMLOGIT				REMLOGIT				FEMLOGIT			
	Market Type				Market Type				Market Type			
	1	2	3	4	1	2	3	4	1	2	3	4
Productivity (LP)	-0.423	0.238**	0.289*	0.775***	-0.448	0.232*	0.231	0.805***	-0.502	0.258**	0.323*	0.826***
	(0.278)	(0.116)	(0.191)	(0.265)	(0.332)	(0.172)	(0.231)	(0.310)	(0.412)	(0.187)	(0.287)	(0.356)
Endowment Position: Long	-0.344	-0.375**	-0.385	-0.796*	-0.460	-0.400*	-0.478	-0.786*	-0.381	-0.395*	-0.426	-0.793
	(0.362)	(0.186)	(0.284)	(0.448)	(0.424)	(0.235)	(0.322)	(0.486)	(0.391)	(0.188)	(0.291)	(0.457)
Sector: Power	1.389***	0.159	0.523*	1.216**	1.432***	0.196	0.560*	1.256**				
	(0.412)	(0.170)	(0.293)	(0.562)	(0.496)	(0.260)	(0.345)	(0.604)				
Firm Age	0.007**	-0.001	-0.001	-0.007	0.007*	-0.001	-0.001	-0.007				
	(0.003)	(0.002)	(0.003)	(0.005)	(0.004)	(0.003)	(0.004)	(0.006)				
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				
Var(α_k)					0.934	1.059	0.663	1.248				
Cov(α_1, α_k)					-	0.553	0.449	-0.067				
Cov(α_2, α_k)					0.553	-	0.812	0.495				
Cov(α_3, α_k)					0.449	0.812	-	0.550				
log likelihood	-831.244				-711.782				-427.642			
Observations	1135				1135				747			
Base outcome	0				0				0			

The multinomial logistic regression with random effects is fit with Stata command *gsem*.

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

POMLOGIT: pooled multinomial logistic regression

REMLOGIT: multinomial logistic regression with random effects

FEMLOGIT: multinomial logit model with fixed effects

Table 3.9.: Permit Trading Amount (Buyers)

	(Phase I)	(Phase II)	(Phase III)
	ln(Amount of Trading)	ln(Amount of Trading)	ln(Amount of Trading)
ln(Revenue/Total Assets)	0.287	0.162	-0.000276
	(0.250)	(0.158)	(0.173)
ln(Employment)	0.280**	0.565***	0.337*
	(0.102)	(0.0752)	(0.190)
Return on Assets	-0.0480***	-0.0179	0.0490***
	(0.0148)	(0.0149)	(0.0126)
Endowment Position: Long	-0.833**	-0.0165	0.360
	(0.386)	(0.208)	(0.329)
Endowment Stock	49.86	20.88	-22.32**
	(30.64)	(13.75)	(8.841)
Family-Owned	-1.160**	-1.149**	-0.519
	(0.484)	(0.545)	(0.696)
Firm Age	0.0148*	0.0111***	0.00384
	(0.00755)	(0.00343)	(0.00529)
Sector: Power	2.256***	2.249***	-0.187
	(0.544)	(0.592)	(0.848)
Market Type 2			-0.0366
			(0.396)
Market Type 3			0.966***
			(0.325)
Market Type 4		0.654**	1.403***
		(0.294)	(0.486)
Industry FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
N	86	260	238
R^2	0.597	0.590	0.585

Notes: The results indicate: (1) larger firms purchase more EUAs; (2) family-Owned firms acquire significantly fewer EUAs; (3) firm age has a small but significantly positive effect on the amount of EUA purchase; (4) firms in power sector buy significantly more EUAs; (5) fewer amount of EUAs are purchased in initial market.

Standard errors in parentheses

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

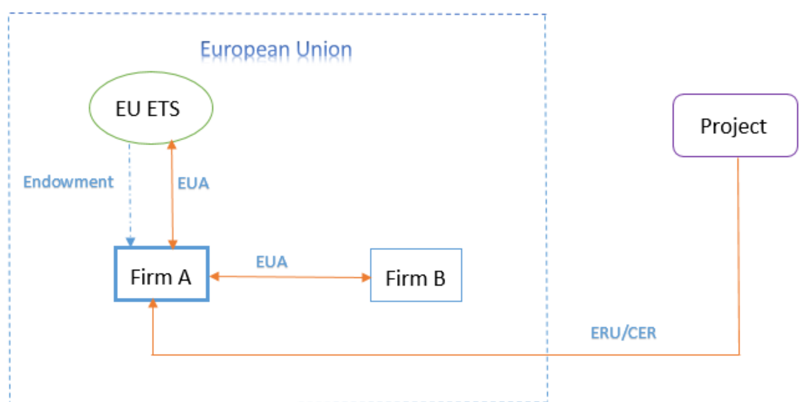


Figure 3.1.: Trading Structure

REFERENCES

Abraham, Filip, Jozef Konings, and Stijn Vanormelingen, "The effect of globalization on union bargaining and price-cost margins of firms," *Review of World Economics*, 2009, *145* (1), 13–36.

Abrell, Jan, Anta Ndoye Faye, and Georg Zachmann, "Assessing the impact of the EU ETS using firm level data," Technical Report, Bruegel working paper 2011.

Ackerberg, Daniel A, Kevin Caves, and Garth Frazer, "Identification properties of recent production function estimators," *Econometrica*, 2015, *83* (6), 2411–2451.

Anderson, Barry and Corrado Di Maria, "Abatement and Allocation in the Pilot Phase of the EU ETS," *Environmental and Resource Economics*, 2011, *48* (1), 83–103.

_ **, Frank Convery, and Corrado Di Maria**, "Technological change and the EU ETS: the case of Ireland," 2011.

Anouliès, Lisa, "Heterogeneous firms and the environment: a cap-and-trade program," *Journal of Environmental Economics and Management*, 2017, *84*, 84–101.

aus dem Moore, Nils, Philipp Großkurth, and Michael Themann, "Multinational corporations and the EU Emissions Trading System: The specter of asset erosion and creeping deindustrialization," *Journal of Environmental Economics and Management*, 2019, *94*, 1–26.

Bae, Hyunhoe, "Do plants decrease pollution reduction efforts during a recession? Evidence from upstate New York chemical plants during the US great recession," *Environmental and Resource Economics*, 2017, *66* (4), 671–687.

Bataller, Maria Mansanet, Julien Chevallier, Morgan Hervé-Mignucci, and Emilie Alberola, "The EUA-sCER spread: compliance strategies and arbitrage in the European carbon market," 2010.

Betz, Regina A and Tobias S Schmidt, "Transfer patterns in Phase I of the EU Emissions Trading System: a first reality check based on cluster analysis," *Climate Policy*, 2016, *16* (4), 474–495.

Branger, Frédéric, Jean-Pierre Ponssard, Oliver Sartor, and Misato Sato, "EU ETS, free allocations, and activity level thresholds: the devil lies in the details," *Journal of the Association of Environmental and Resource Economists*, 2015, *2* (3), 401–437.

Brunel, Claire and Arik Levinson, "Measuring the stringency of environmental regulations," *Review of Environmental Economics and Policy*, 2016, *10* (1), 47–67.

Buckley, Peter J, "Foreign direct investment by small-and medium-sized enterprises: the theoretical background," in "The multinational enterprise," Springer, 1989, pp. 24–45.

Calel, Raphael, "Adopt or innovate: Understanding technological responses to cap-and-trade," 2018.

— **and Antoine Dechezlepretre**, "Environmental policy and directed technological change: evidence from the European carbon market," *Review of economics and statistics*, 2016, *98* (1), 173–191.

Cao, Jing, Larry D Qiu, and Mohan Zhou, "Who invests more in advanced abatement technology? Theory and evidence," *Canadian Journal of Economics/Revue canadienne d'économique*, 2016, *49* (2), 637–662.

Cassiman, Bruno and Stijn Vanormelingen, "Profiting from innovation: Firm level evidence on markups," *Available at SSRN 2381996*, 2013.

Chan, Hei Sing (Ron), Shanjun Li, and Fan Zhang, "Firm competitiveness and the European Union emissions trading scheme," *Energy Policy*, 2013, *63*, 1056–1064.

Chau, Frankie, Jing-Ming Kuo, and Yukun Shi, "Arbitrage opportunities and feedback trading in emissions and energy markets," *Journal of International Financial Markets, Institutions and Money*, 2015, *36*, 130–147.

Cherniwchan, Jevan, Brian R Copeland, and M Scott Taylor, "Trade and the environment: New methods, measurements, and results," *Annual Review of Economics*, 2017, *9*, 59–85.

Cofala, Janusz and Sanna Syri, "Sulfur emissions, abatement technologies and related costs for Europe in the RAINS model database," 1998.

Copeland, Brian R and M Scott Taylor, "Trade, growth, and the environment," *Journal of Economic literature*, 2004, *42* (1), 7–71.

— **and** —, *Trade and the environment: Theory and evidence*, Princeton University Press, 2005.

Cui, Jingbo, Harvey E Lapan, and GianCarlo Moschini, "Are exporters more environmentally friendly than non-exporters? Theory and evidence," 2012.

Cullenward, Danny and Andy Coghlan, "Structural oversupply and credibility in California's carbon market," *The Electricity Journal*, 2016, *29* (5), 7–14.

Dechezleprêtre, Antoine, Daniel Nachtigall, and Frank Venmans, "The joint impact of the European Union emissions trading system on carbon emissions and economic performance," 2018.

Delarue, Erik D, A Denny Ellerman, and WILLIAM D D'HAESELEER, "Short-term CO2 abatement in the European power sector: 2005–2006," *Climate Change Economics*, 2010, *1* (02), 113–133.

Dixit, Avinash K and Joseph E Stiglitz, "Monopolistic competition and optimum product diversity," *The American economic review*, 1977, *67* (3), 297–308.

Dobbelaere, Sabien and Jacques Mairesse, "Panel data estimates of the production function and product and labor market imperfections," *Journal of Applied Econometrics*, 2013, *28* (1), 1–46.

Earnhart, Dietrich and Lubomir Lizal, "Effect of corporate economic performance on firm-level environmental performance in a transition economy," *Environmental and resource Economics*, 2010, *46* (3), 303–329.

Egenhofer, Christian, Monica Alessi, Anton Georgiev, and Noriko Fujiwara, "The EU Emissions Trading System and Climate Policy towards 2050: Real incentives to reduce emissions and drive in-novation? CEPS Special Report, Centre for European Policy Studies," 2011.

Ellerman, A Denny and Barbara K Buchner, "Over-allocation or abatement? A preliminary analysis of the EU ETS based on the 2005–06 emissions data," *Environmental and Resource Economics*, 2008, *41* (2), 267–287.

— and Meghan McGuinness, "CO2 Abatement in the UK Power Sector: Evidence from the EU ETS Trial Period," 2008.

—, Frank J Convery, and Christian De Perthuis, *Pricing carbon: the European Union emissions trading scheme*, Cambridge University Press, 2010.

Feilhauer, Stephan Marvin and A Denny Ellerman, "A Top-down and Bottom-up look at Emissions Abatement in Germany in response to the EU ETS," 2008.

Forslid, Rikard, Toshihiro Okubo, and Karen Helene Ulltveit-Moe, "Why are firms that export cleaner? International trade, abatement and environmental emissions," *Journal of Environmental Economics and Management*, 2018, *91*, 166–183.

Goulder, Lawrence H and Ian WH Parry, "Instrument choice in environmental policy," *Review of environmental economics and policy*, 2008, *2* (2), 152–174.

Guo, Jianfeng, Bin Su, Guang Yang, Lianyong Feng, Yinpeng Liu, and Fu Gu, "How Do Verified Emissions Announcements Affect the Comoves between Trading Behaviors and Carbon Prices? Evidence from EU ETS," *Sustainability*, 2018, *10* (9), 3255.

Hailu, Atakelty and Terrence S Veeman, "Environmentally sensitive productivity analysis of the Canadian pulp and paper industry, 1959-1994: an input distance function approach," *Journal of environmental economics and management*, 2000, *40* (3), 251–274.

Hall, Robert E, Olivier Jean Blanchard, and R Glenn Hubbard, "Market structure and macroeconomic fluctuations," *Brookings papers on economic activity*, 1986, *1986* (2), 285–338.

Hanemann, W Michael, "Welfare evaluations in contingent valuation experiments with discrete responses," *American journal of agricultural economics*, 1984, *66* (3), 332–341.

Heindl, Peter and Benjamin Lutz, "Carbon management: evidence from case studies of German firms under the EU ETS," 2012.

Holladay, J Scott, "Exporters and the environment," *Canadian Journal of Economics/Revue canadienne d'économique*, 2016, *49* (1), 147–172.

Huang, Ying, Lei Liu, Xiaoming Ma, and Xiaofeng Pan, "Abatement technology investment and emissions trading system: a case of coal-fired power industry of Shenzhen, China," *Clean Technologies and Environmental Policy*, 03 2014, *17*, 811–817.

Isaksson, Lena Höglund, "Abatement costs in response to the Swedish charge on nitrogen oxide emissions," *Journal of Environmental Economics and Management*, 2005, *50* (1), 102–120.

Jaraitė, Jūratė, Frank Convery, and Corrado Di Maria, "Transaction costs for firms in the EU ETS: lessons from Ireland," *Climate Policy*, 2010, *10* (2), 190–215.

Jaraitė-Kažukauskė, Jūratė and Andrius Kažukauskas, "Do transaction costs influence firm trading behaviour in the european emissions trading system?," *Environmental and Resource Economics*, 2015, *62* (3), 583–613.

Keohane, Nathaniel, Annie Petsonk, and Alex Hanafi, "Toward a club of carbon markets," *Climatic Change*, 2017, *144* (1), 81–95.

Kettner, Claudia, Daniela Kletzan-Slamanig, and Angela Köppl, "The EU Emission Trading Scheme. Sectoral Allocation Patterns and Factors Determining Emission Changes," Technical Report, WIFO Working Papers 2013.

Klemetsen, Marit E, Knut Einar Rosendahl, and Anja Lund Jakobsen, "The impacts of the EU ETS on Norwegian plants' environmental and economic performance," Technical Report, Discussion Papers 2016.

Konishi, Yoshifumi and Nori Tarui, "Emissions trading, firm heterogeneity, and intra-industry reallocations in the long run," *Journal of the Association of Environmental and Resource Economists*, 2015, *2* (1), 1–42.

Kozluk, Tomasz and Vera Zipperer, "Environmental policies and productivity growth," *OECD Journal: Economic Studies*, 2015, *2014* (1), 155–185.

Levinsohn, James and Amil Petrin, "Estimating production functions using inputs to control for unobservables," *The review of economic studies*, 2003, *70* (2), 317–341.

Levinson, Arik and M Scott Taylor, "Unmasking the pollution haven effect," *International economic review*, 2008, *49* (1), 223–254.

Liu, Yin-Peng, Jian-Feng Guo, and Ying Fan, "A big data study on emitting companies' performance in the first two phases of the European Union Emission Trading Scheme," *Journal of cleaner production*, 2017, *142*, 1028–1043.

Loecker, Jan De and Frederic Warzynski, "Markups and firm-level export status," *American economic review*, 2012, *102* (6), 2437–71.

_, Pinelopi K Goldberg, Amit K Khandelwal, and Nina Pavcnik, "Prices, markups, and trade reform," *Econometrica*, 2016, *84* (2), 445–510.

Löschel, Andreas, Karl Ludwig Brockmann, Peter Heindl, Benjamin Lutz, and Jan Schumacher, "KfW/ZEW CO2 Barometer 2011: Hoher Anpassungsbedarf im EU-Emissionshandel ab 2013–deutliche Defizite bei der Vorbereitung in den Unternehmen," Technical Report, KfW/ZEW CO2 Barometer 2011.

Marin, Giovanni, Marianna Marino, and Claudia Pellegrin, "The impact of the European Emission Trading Scheme on multiple measures of economic performance," *Environmental and resource economics*, 2018, *71* (2), 551–582.

Martin, Ralf, Mirabelle Muûls, and Ulrich J Wagner, "Trading behavior in the eu emissions trading scheme," *Available at SSRN 2362810*, 2014.

_, _, and Ulrich Wagner, "Carbon markets, carbon prices and innovation: Evidence from interviews with managers," 2013.

McFadden, Daniel, *Conditional Logit Analysis of Qualitative Choice Behavior*, New York: New York: Academic Press,

Melitz, Marc J, "The impact of trade on intra-industry reallocations and aggregate industry productivity," *econometrica*, 2003, *71* (6), 1695–1725.

Michaelowa, Axel and Frank Jotzo, "Transaction costs, institutional rigidities and the size of the clean development mechanism," *Energy policy*, 2005, *33* (4), 511–523.

Montgomery, W David, "Markets in licenses and efficient pollution control programs," *Journal of economic theory*, 1972, *5* (3), 395–418.

Naegele, Helene, "Offset credits in the EU ETS: A quantile estimation of firm-level transaction costs," *Environmental and resource economics*, 2018, *70* (1), 77–106.

National Academy of Engineering, *The Ecology of Industry: Sectors and Linkages*, Washington, DC: The National Academies Press, 1998.

Newell, Richard G and Robert N Stavins, "Cost heterogeneity and the potential savings from market-based policies," *Journal of Regulatory Economics*, 2003, *23* (1), 43–59.

Otto, Vincent M and John Reilly, "Directed technical change and the adoption of CO2 abatement technology: the case of CO2 capture and storage," *Energy Economics*, 2008, *30* (6), 2879–2898.

Petrick, Sebastian and Ulrich J Wagner, "The impact of carbon trading on industry: Evidence from German manufacturing firms," *Available at SSRN 2389800*, 2014.

Pforr, Klaus, "femlogit—implementation of the multinomial logit model with fixed effects," *The Stata Journal*, 2014, *14* (4), 847–862.

Reinhard, Stijn, CA Knox Lovell, and Geert Thijssen, "Econometric estimation of technical and environmental efficiency: an application to Dutch dairy farms," *American Journal of Agricultural Economics*, 1999, *81* (1), 44–60.

Sanin, María Eugenia, Francesco Violante, and María Mansanet-Bataller, "Understanding volatility dynamics in the EU-ETS market," *Energy Policy*, 2015, *82*, 321–331.

Sartzetakis, Eftichios, "Tadeable Emission Permits Regulations in the Presence of Imperfectly Competitive Product Markets: Welfare Implications," *Environmental Resource Economics*, 1997, *9* (01), 65–81.

Sato, Misato, Marta Ciszawska, Timothy Laing et al., "Demand for offsetting and insetting in the EU Emissions Trading System," 2016.

Shadbegian, Ronald J and Wayne B Gray, "What determines environmental performance at paper mills? The roles of abatement spending, regulation, and efficiency," *Topics in economic analysis & policy*, 2003, *3* (1).

Shapiro, Joseph S and Reed Walker, "Why is pollution from US manufacturing declining? The roles of environmental regulation, productivity, and trade," *American Economic Review*, 2018, *108* (12), 3814–54.

Siotis, Georges, "Competitive pressure and economic integration: An illustration for Spain, 1983–1996," *International Journal of Industrial Organization*, 2003, *21* (10), 1435–1459.

Trotignon, Raphael, "Combining cap-and-trade with offsets: lessons from the EU-ETS," *Climate Policy*, 2012, *12* (3), 273–287.

Veith, Stefan, Jörg R Werner, and Jochen Zimmermann, "Capital market response to emission rights returns: Evidence from the European power sector," *Energy economics*, 2009, *31* (4), 605–613.

Wagner, Ulrich and Sebastian Petrick, "The impact of carbon trading on industry: Evidence from German manufacturing firms," 2014.

Wagner, Ulrich J, Mirabelle Muûls, Ralf Martin, and Jonathan Colmer, "The Causal Effect of the European Union Emissions Trading Scheme: Evidence from French Manufacturing Plants," 2014.

_ , _ , _ , and _ , "The causal effects of the European Union Emissions Trading Scheme: evidence from French manufacturing plants," in "in" Citeseer 2014.

Yokoo, H-F, "Heterogeneous firms, the Porter hypothesis and trade," 2009.

Zaklan, Aleksandar, "Why do emitters trade carbon permits? Firm-level evidence from the European Emission Trading Scheme," 2013.

A. A THEORETICAL FRAMEWORK OF EMISSION REDUCTION AND PERMIT TRADE WITH HETEROGENEOUS FIRMS

We provide a simple framework to discuss factors that may influence firms' trading behaviors. Note that our model is intended to serve as a benchmark to provide some economic reasoning to the empirical findings and intentionally ignore less important details. Our primary question is how firms would exhibit heterogeneous trading patterns based on their characteristics or types.

Firms Assume that there are N firms indexed by $i = 1, 2, 3, ..., N$. The emission target is $\bar{E}$, which is exogenous determined by the regulatory authority. The cost of abatement is $c(r_i, \theta_i)$, where r_i is the emission reduction of firm i and the θ_i is the firm's type. In our context, we use a firm's productivity to represent a firm's type. The abatement cost of a firm takes the form of:

$$c(r_i, \theta_i) = \theta_i r_i^2. \tag{A.1}$$

The emission reduction r_i is the difference between the required and the normal level of emission level e_i. We further assume that, if a firm is more productive, then the productive parameter θ_i is smaller so that a higher productive firm is more cost effective in reducing emssion. Assume that a firm earns D_i ($D_i > 0$) permits in the initial market and trade t_i in the secondary market ($t_i > 0$ means net purchase and $t_i < 0$ means net seller). Note that the emission level e_i is also determined by the firms' productivity parameter θ_i. The firm i is subject to the permit constraint:

$$D_i + t_i = e_i(\theta_i) - r_i, \tag{A.2}$$

indicating that the firm i needs to obtain permits from the initial market or the secondary market to cover the emission difference between the normal emission and the emission reduction.

Secondary Market The secondary market price is determined by the emission cap $\bar{E}$ and the aggregated demand function $\sum_i^N D_i$. In the equilibrium, we assume that the price in the secondary market is p_t. The firm i's cost function:

$$C_{i2} = \theta_i(e_i(\theta_i) - D_i - t_i)^2 + p_t t_i. \tag{A.3}$$

Taking the first derivative w.r.t. t_i, we have,

$$t_i^* = e_i(\theta_i) - D_i - \frac{1}{2\theta_i} p_t. \tag{A.4}$$

Therefore, we have,

$$\sum_i t_i^* = \sum_i e_i(\theta) - \sum_i D_i - \sum_i \frac{1}{2\theta_i} p_t. \tag{A.5}$$

According to market clearing condition $\sum_i^N D_i = \bar{E}$, the above equation becomes:

$$0 = \sum_i e_i(\theta_i) - \bar{E} - \sum_i \frac{1}{2\theta_i} p_t. \tag{A.6}$$

Thus, the secondary market price p_t is

$$p_t = \frac{\sum_i e_i(\theta_i) - \bar{E}}{\sum_i \frac{1}{2\theta_i}}. \tag{A.7}$$

Substituting the above equation into the optimal trading t_i^* in the secondary stage, we have

$$t_i^* = e_i(\theta_i) - D_i - \frac{1}{2\theta_i} \frac{\sum_i e_i(\theta_i) - \bar{E}}{\sum_i \frac{1}{2\theta_i}} \tag{A.8}$$

The optimal abatement r^* is

$$r_i^* = e_i(\theta_i) - D_i - t_i^* = \frac{1}{2\theta_i} \frac{\sum_i e_i(\theta_i) - \bar{E}}{\sum_i \frac{1}{2\theta_i}} = \frac{p_t}{2\theta_i}. \tag{A.9}$$

Equations A.8 and A.9 provide explicit solutions for the optimal trading amount t_i^* and abatement r_i^* for firm i based on our assumptions. Note that our results show that a productive firm will also abate more as $\frac{\partial r_i^*}{\partial \theta} < 0$ based on equation A.9. However, the relationship between productivity and the optimal trading amount is less obvious.

If permit prices are given, we take the first order derivatives of t_i^* with respect to $\frac{1}{\theta_i}$ based on equation A.4:

$$\frac{\partial t_i^*}{\partial \frac{1}{\theta_i}} = e_i' - \frac{p_t}{2} \tag{A.10}$$

The effect of productivity on optimal trading quantity depends on the difference between firm's productivity impact on level of emissions, denoted as e_i', and permit price, p_t. $e_i' > 0$ since more productive firms emit more. The ambiguous net effect of productivity on optimal trading quantity highlights the importance of firms' trading market choices. The current system with multiple trade markets and trading options has created price differentiation, which are essential when taking account of firm heterogeneity in permit trading. Keep firms' emission abatement efficiency fixed, productivity has a positive effect on trading amount in a market where the permit price is relatively low. While, productivity has a negative effect on trading amount in a market where the permit price is relatively high. We next discuss these two situations.

The situation when more productive firms trade a larger amount of permits:

If $0 < p_t < 2e_i'$, then,

$$e_i' - \frac{p_t}{2} > 0.$$

The situation when more productive firms trade a smaller amount of permits:

If $p_t > 2e_i'$, then,

$$e_i' - \frac{p_t}{2} < 0.$$

In this paper, we include two types of permits: EUAs in the EU market and offsets in the international market. According to the price patterns from (Naegele, 2018), offsets have always traded at a positive discount from EUAs. Since permit prices vary in different trading markets, we expect that productivity affects firms' trading behaviors differently in each market based on the our discussions of equation A.4.

Initial Market The price in the initial market is determined through a uniform price sealed-bid auction. Still, assume the same N firms are competing for the initial permits $\bar{E}$. Each firm submits the demand curve D_i. We denote the price in the initial market as p_D. The firm's cost is

$$C_{i1} = p_D(D_i)D_i, \tag{A.11}$$

and the total profit is

$$C_i = \theta_i(e_i - D_i - t_i)^2 + p_t t_i + p_D(D_i)D_i. \tag{A.12}$$

According to equations A.1 and A.2, the firm's marginal value of having one more unit of permit in the initial market is

$$p_D(D_i) = 2\theta_i(e_i - D_i - t_i). \tag{A.13}$$

Therefore, according to market clearing condition $\sum_i^N D_i = \bar{E}$, the above equation becomes,

$$p_D = \frac{\sum_i e_i - \bar{E}}{\sum_i \frac{1}{2\theta_i}}. \tag{A.14}$$

We assume there is an additional benefit/cost to participate in the initial market, denoted by $F(\theta_i, D)$. The total cost equation becomes

$$C_i = \theta_i(e_i - D_i - t_i)^2 + p_t t_i + p_D(D_i)D_i + F(\theta_i, D_i), \tag{A.15}$$

and the FOC becomes

$$p_D - 2\theta_i(e_i - D_i - t_i) + F_d(\theta_i, D_i) = 0. \tag{A.16}$$

Therefore,

$$p_D = 2\theta_i(e_i - D_i - t_i) - F_d(\theta_i, D_i). \tag{A.17}$$

According to market clearing condition $\sum_i^N D_i = \bar{E}$, the above equation becomes

$$p_D = \frac{\sum_i e_i - \bar{E} - F_d(\theta_i, D_i)}{\sum_i \frac{1}{2\theta_i}}. \tag{A.18}$$

Depending on the sign of $F_d(\theta_i, D_i)$, the initial market and the second market price may differ.

According to the above equation A.18, the nature of $F_d(\theta_i, D_i)$ is important in our model prediction. Two factors are identified in the literature to significantly influence the trading behaviors. First is the transaction cost and the entry cost in different markets (Naegele, 2018). According to equation A.3, when the cost is not a function of the trading amount t (e.g., a lump sum entry cost), the optimal trading is unlikely to change. However, when the trading cost is a function of the trading volume, the optimal trading amount will change with the cost. In addition, the information availability also impacts the optimal trading amount. Existing literature has shown that increased information availability reduces uncertainties and risks of trading (Guo et al., 2018). As a result, firms' market choices are more sensitive to the entry costs, while trading amounts are subject to the influence of transaction costs. While we did not model international market specifically, we can consider the international market as a special case of the secondary market. In our context, the international market is likely to have a high entry cost compared to the initial market and the secondary market. In terms of the transaction cost, the initial market has a smaller transaction per unit compared to the secondary market. Another potential factor is the influence of information. In the EU ETS, the amount of credits sold each year is public information in the primary market. However, the information is more uncertain in the secondary market. On the international market, the available credits are project based. The difference in the accessibility to information also leads to different market participation and trading amount decisions.

B. TABLES

Table B.1.: Number of Matched EU ETS Firms by Country and Sector

Country	N_{total}	N_{match}	N_{lit}
Austria	140	77	83
Belgium	287	139	193
Germany	789	200	429
Bulgaria	147	62	—
Croatia	42	41	—
Czech Republic	298	130	239
Denmark	271	135	53
Estonia	40	30	13
Finland	195	140	61
France	341	201	119
Hungary	204	91	127
Ireland	100	43	—
Italy	532	211	335
Latvia	99	66	21
Lithuania	85	62	—
Netherlands	385	77	105
Poland	329	156	285
Portugal	285	171	171
Romania	230	83	—
Slovak Republic	162	145	109
Slovenia	97	54	65
Spain	718	442	641
Sweden	290	181	118
UK	366	250	278
Total	6432	3186	3445
Sector	N_{total}	N_{match}	N_{lit}
Pulp and Paper		761	
Petroleum and Coke		38	
Chemicals		67	
Non-metallic Minerals		730	
Basic Metals		166	
Power		312	
Others		1112	
Total		3,186	

N_{lit}: the matching from Marin et al. (2018)

Table B.2.: Explaining Emission Intensity in the EU ETS (DWL)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OLS	OLS	OLS	IV	IV	IV	FD	FD	FD
log(productivity)	-0.467***	-0.350***	-0.324***	-0.484***	-0.309***	-0.280***	-0.207***	-0.238***	-0.327***
	(0.109)	(0.078)	(0.083)	(0.014)	(0.026)	(0.027)	(0.030)	(0.036)	(0.0368)
log(policy)	-0.485***	-0.067***	-0.079***	-0.734***	-0.075***	-0.093***	-0.020**	-0.021***	-0.021**
	(0.056)	(0.015)	(0.016)	(0.039)	(0.016)	(0.016)	(0.009)	(0.009)	(0.009)
Country FE	Yes	No	No	Yes	No	No			
Industry FE	Yes	No	No	Yes	No	No			
Year FE	Yes	Yes	No	Yes	Yes	No			
Firm FE	No	Yes	Yes	No	Yes	Yes			
Country-Industry-Year FE	No	No	Yes	No	No	Yes			
TFP_{ACF}							✓		
TFP_{LP}								✓	
TFP_{DLW}	✓	✓	✓	✓	✓	✓			✓
N	10552	10552	10552	9874	9874	9874	9431	9431	9431
R^2	0.569	0.943	0.947	-	-	-	-	-	-

Notes: Standard errors in parentheses and clustered in firm level. I adopt log value of capital and depreciation as instrument variables.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.3.: Explaining Emission Intensity in the EU ETS (LP)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OLS	OLS	OLS	IV	IV	IV	FD	FD	FD
log(productivity)	-0.328**	-0.235**	-0.267**	-0.354***	-0.168***	-0.201***	-0.238***	-0.658***	-0.327***
	(0.114)	(0.148)	(0.147)	(0.0290)	(0.0366)	(0.0358)	(0.0356)	(0.0393)	(0.0368)
log(policy)	-0.409***	-0.0821***	-0.0795***	-0.863***	-0.0917***	-0.0978***	-0.0207**	-0.0247***	-0.0212**
	(0.0725)	(0.0147)	(0.0149)	(0.0450)	(0.0169)	(0.0166)	(0.0089)	(0.0087)	(0.0089)
Country FE	Yes	No	Yes	Yes	No	Yes			
Industry FE	Yes	No	No	Yes	No	No			
Year FE	Yes	Yes	Yes	Yes	Yes	Yes			
Firm FE	No	Yes	Yes	No	Yes	Yes			
TFP_{LP}	✓	✓	✓	✓	✓	✓	✓		
TFP_{FE}								✓	
TFP_{OLS}									✓
N	10552	10552	10552	9874	9874	9874	10552	10552	10552
R^2	0.429	0.928	0.930	-	-	-	-	-	-

Notes: Standard errors in parentheses and clustered in firm level. I adopt log value of capital and depreciation as instrument variables.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.4.: The Decomposition of Actual CO_2 Emission Intensity (ACF)

Time Period	(1) $\overline{\Delta ln(\frac{e}{q})}$	(2) $\overline{\Delta ln(T)}$	(3) $\beta_2\overline{\Delta ln(T)}$	(4) $\overline{\Delta ln(1-\gamma)}$	(5) $\overline{\Delta ln(f)}$	(6) $\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}$	(7) $\overline{\Delta ln(\frac{e}{q})_f}$
2005-2006	-0.151	0.100	-0.002	-0.098	-0.440	-0.021	0.018
2006-2007	-0.041	0.164	-0.003	-0.161	-0.722	-0.034	0.030
2007-2008	-0.092	-0.987	0.020	0.967	4.343	0.204	-0.183
2008-2009	-0.044	0.322	-0.006	-0.316	-1.417	-0.066	0.060
2009-2010	-0.077	-0.067	0.001	0.066	0.295	0.014	-0.012
2010-2011	-0.177	-0.017	0.000	0.017	0.075	0.004	-0.003
2011-2012	-0.075	-0.425	0.009	0.417	1.870	0.088	-0.079
2012-2013	-0.003	0.592	-0.012	-0.580	-2.605	-0.122	0.110
2013-2014	-0.043	0.010	0.000	-0.010	-0.044	-0.002	0.002
2014-2015	-0.022	0.009	0.000	-0.009	-0.040	-0.002	0.002
2015-2016	0.025	-0.006	0.000	0.006	0.026	0.001	-0.001
Phase 1 (2005-2007)	-0.192	0.263	-0.005	-0.258	-1.157	-0.054	0.049
			[2.74%]			[28.24%]	
Phase 2 (2008-2012)	-0.373	-0.188	0.004	0.184	0.827	0.039	-0.035
			[-1.01%]				[9.32%]
Phase 3 (2013-2016)	-0.040	0.014	-0.0003	-0.014	-0.062	-0.003	0.003
			[0.70%]			[7.22%]	
Total (2005-2016)	-0.605	0.090	-0.002	-0.088	-0.396	-0.019	0.017
						[3.07%]	

Notes: β_2 is estimated by the first difference, the value is -0.020. The brackets of column (3) report the percentage value of $\frac{\beta_2\overline{\Delta ln(T)}}{\overline{\Delta ln(\frac{e}{q})}}$, the brackets of column (6) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}}{\overline{\Delta ln(\frac{e}{q})}}$, and the brackets of column (7) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_f}}{\overline{\Delta ln(\frac{e}{q})}}$.

Table B.5.: The Decomposition of the Predicted CO_2 Emissions (ACF)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Time Period	ΔT	ΔQ	$\Delta\frac{\hat{e}}{q}_{total}$	$\Delta\frac{\hat{e}}{q}_{1-\gamma}$	$\Delta\frac{\hat{e}}{q}_{f}$	$\Delta\hat{e}_{total}$	$\Delta\hat{e}_{1-\gamma}$	$\Delta\hat{e}_{f}$	Δe_{total}
2005-2006	-0.172	-49.700	0.019	0.028	-0.008	-132.028	-132.017	-0.011	12.613
2006-2007	-0.851	34.850	0.095	0.136	-0.041	46.756	46.834	-0.078	11.768
2007-2008	53.946	19.628	-6.042	-8.649	2.586	22.374	16.755	5.619	-11.645
2008-2009	29.194	-11.225	-3.270	-4.681	1.399	-28.652	-30.342	1.690	-36.950
2009-2010	13.234	23.442	-1.482	-2.122	0.634	37.638	34.760	2.878	21.105
2010-2011	16.506	19.968	-1.849	-2.646	0.791	37.592	33.870	3.723	-10.854
2011-2012	30.867	-1.236	-3.457	-4.949	1.479	-11.596	-14.424	2.828	-17.592
2012-2013	-59.031	-37.417	6.612	9.464	-2.829	-79.134	-69.645	-9.489	24.063
2013-2014	0.045	46.730	-0.005	-0.007	0.002	74.125	70.775	3.350	-0.626
2014-2015	1.147	-34.149	-0.128	-0.184	0.055	-79.687	-76.170	-3.517	0.941
2015-2016	0.755	29.094	-0.085	-0.121	0.036	44.373	42.278	2.096	1.699
Phase 1 (2005-2007)	52.922	4.778	-5.927	-8.485	2.537	-62.897	-68.427	5.530	24.381
						[-23.67%]			[9.18%]
Phase 2 (2008-2012)	30.770	-6.468	-3.446	-4.933	1.475	-44.151	-45.781	1.630	-55.936
						[-16.62%]			[-21.05%]
Phase 3 (2013-2016)	1.947	41.675	-0.218	-0.312	0.093	38.812	36.883	1.929	26.077
						[14.61%]			[9.81%]
Total (2005-2016)	85.639	39.985	-9.592	-13.730	4.105	-68.237	-77.326	9.089	-5.478
						[-25.68%]			[-2.06%]

Notes: The columns (1)-(5) are percent change. The columns (6)-(9) are amount change in an unit of $MtCO_2e$.

Table B.6.: The Decomposition of Actual CO_2 Emission Intensity (LP)

Time Period	(1) $\overline{\Delta ln(\frac{e}{q})}$	(2) $\overline{\Delta ln(T)}$	(3) $\beta_2\overline{\Delta ln(T)}$	(4) $\overline{\Delta ln(1-\gamma)}$	(5) $\overline{\Delta ln(f)}$	(6) $\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}$	(7) $\overline{\Delta ln(\frac{e}{q})_f}$
2005-2006	-0.151	0.100	-0.002	-0.098	-0.490	-0.024	0.022
2006-2007	-0.041	0.164	-0.003	-0.161	-0.803	-0.039	0.036
2007-2008	-0.092	-0.987	0.020	0.967	4.833	0.235	-0.214
2008-2009	-0.044	0.322	-0.007	-0.315	-1.577	-0.077	0.070
2009-2010	-0.077	-0.067	0.001	0.066	0.328	0.016	-0.015
2010-2011	-0.177	-0.017	0.000	0.017	0.083	0.004	-0.004
2011-2012	-0.075	-0.425	0.009	0.416	2.081	0.101	-0.092
2012-2013	-0.003	0.592	-0.012	-0.580	-2.899	-0.141	0.129
2013-2014	-0.043	0.010	0.000	-0.010	-0.049	-0.002	0.002
2014-2015	-0.022	0.009	0.000	-0.009	-0.044	-0.002	0.002
2015-2016	0.025	-0.006	0.000	0.006	0.029	0.001	-0.001
Phase 1 (2005-2007)	-0.192	0.263	-0.005	-0.258	-1.288	-0.063	0.057
			[2.84%]			[32.58%]	
Phase 2 (2008-2012)	-0.373	-0.188	0.004	0.184	0.921	0.045	-0.041
			[-1.04%]				[10.95%]
Phase 3 (2013-2016)	-0.040	0.014	-0.0003	-0.014	-0.069	-0.003	0.003
			[0.73%]			[8.33%]	
Total (2005-2016)	-0.605	0.090	-0.002	-0.088	-0.441	-0.021	0.020
			[0.31%]			[3.54%]	

Notes: β_2 is estimated by the first difference, the value is -0.0207. The brackets of column (3) report the percentage value of $\frac{\beta_2\overline{\Delta ln(T)}}{\Delta ln(\frac{e}{q})}$, the brackets of column (6) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_{1-\gamma}}}{\Delta ln(\frac{e}{q})}$, and the brackets of column (7) report the percentage value of $\frac{\overline{\Delta ln(\frac{e}{q})_f}}{\Delta ln(\frac{e}{q})}$.

Table B.7.: The Decomposition of the Predicted CO_2 Emissions (LP)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Time Period	ΔT	ΔQ	$\Delta \frac{\hat{e}}{q}_{total}$	$\Delta \frac{\hat{e}}{q}_{1-\gamma}$	$\Delta \frac{\hat{e}}{q}_{f}$	$\Delta \hat{e}_{total}$	$\Delta \hat{e}_{1-\gamma}$	$\Delta \hat{e}_{f}$	Δe_{total}
2005-2006	-0.172	-49.7	0.017	0.034	-0.017	-132.031	-132.008	-0.023	12.613
2006-2007	-0.851	34.85	0.085	0.17	-0.085	46.737	46.898	-0.161	11.768
2007-2008	53.946	19.628	-5.395	-10.789	5.395	23.768	12.138	11.63	-11.645
2008-2009	29.194	-11.225	-2.919	-5.839	2.919	-28.211	-31.624	3.414	-36.950
2009-2010	13.234	23.442	-1.323	-2.647	1.323	38.375	32.503	5.872	21.105
2010-2011	16.506	19.968	-1.651	-3.301	1.651	38.554	30.992	7.563	-10.854
2011-2012	30.867	-1.236	-3.087	-6.173	3.087	-10.834	-16.469	5.635	-17.592
2012-2013	-59.031	-37.417	5.903	11.806	-5.903	-81.629	-62.498	-19.131	24.063
2013-2014	0.045	46.73	-0.004	-0.009	0.004	74.957	68.034	6.924	-0.626
2014-2015	1.147	-34.149	-0.115	-0.229	0.115	-80.559	-73.286	-7.273	0.941
2015-2016	0.755	29.094	-0.076	-0.151	0.076	44.895	40.569	4.327	1.699
Phase 1 (2005-2007)	52.922	4.778	-5.292	-10.584	5.292	-61.525	-72.971	11.445	24.381
						[-23.16%]			[9.18%]
Phase 2 (2008-2012)	30.77	-6.468	-3.077	-6.154	3.077	-43.745	-47.097	3.353	-55.937
						[-16.46%]			[-20.09%]
Phase 3 (2013-2016)	1.947	41.675	-0.195	-0.389	0.195	39.293	35.316	3.978	26.078
						[14.79%]			[10.10%]
Total (2005-2016)	85.639	39.985	-8.564	-17.128	8.564	-65.976	-84.752	18.776	-5.478
						[-24.83%]			[-0.81%]

Notes: The columns (1)-(5) are percent change. The columns (6)-(9) are amount change in an unit of $MtCO_2e$.

Table B.8.: Sectors and NACE Codes

Power and Heat	Pulp and Paper	Non-metallic Minerals	Basic Metals	Chemicals	Petroleum and Coke
35	17	23	24	20	19
Combustion of fuels	Paper	Ceramics	Iron and Steel	Bulk chemicals	Coke
Combustion	Paper or cardboard	Glass	Pig iron or steel	Ammonia	Coke ovens
	Pulp	Gypsum or plasterboard	Ferrous metals	Carbon black	Refining of mineral oil
	Combustion of paper	Bricks and Ceramics	Non-ferrous metals	Hydrogen and synthesis gas	Refining
		Cement and Lime	Metal ore roasting or sintering	Nitric acid	
		Cement clinker	Primary aluminium	Soda ash and sodium bicarbonate	
		Lime	Secondary aluminium		
		Mineral wool			