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Corporate Emissions-Trading Behaviour During the First Decade of the EU ETS

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Abstract
This study analyses factors related to allowance-trading behaviour for the first ten years of the existence of the European Union Emissions Trading System (EU ETS). Our empirical analysis employs a dataset that combines information on trading activities for more than 6000 companies with company characteristics. Indicators of trading activity include the volume and the number of transactions as well as the usage of intermediaries and of derivatives markets. For 2005–2014 and for the individual trading periods, we find that trading behaviour is related to the size of a company, its net position (the difference between free allocations and verified emissions), its sector affiliation, productivity, and location. We also find evidence that trading-related transaction costs affect trading activity in the EU ETS in all trading periods. Our results further suggest that net buyers (companies whose verified emissions exceed free allocations in a given year) are more likely to participate in emissions trading and to trade at higher volumes than net sellers are. We explain this asymmetry in behaviour—which might lead to a violation of Coase's independence property—by potential asymmetries in the actual or perceived opportunity costs of holding allowances between net sellers and net buyers.

Keywords Climate policy · Emissions trading · EU ETS · Transaction behaviour · Transaction costs

Abbreviations

AOA	Aircraft operator account
CER	Certified emission reductions

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CITL	Community Independent Transaction Log
CRE	Correlated random-effects estimator
EEX	European Energy Exchange
ERU	Emission reduction units
EUA	EU allowances
EU ETS	European Union Emissions Trading System
EUTL	European Union Transaction Log
GHG	Greenhouse gases
OHA	Operator holding account
PHA	Person holding account
TA	Trading account

1 Introduction

Since its inception in 2005, the European Union Emissions Trading System (EU ETS) has been one of the cornerstones of EU climate policy, set up to help the EU meet its climate targets in the covered sectors at the lowest cost. Regulating emissions by energy and energy-intensive industries and aircraft operators, a large number of companies with more than 11,000 installations formulate individual trading decisions and strategies vis-à-vis the EU carbon market. Over time, the EU ETS has grown as more countries and types of greenhouse gases (GHG) and activities are covered by the system. Starting with the first trading period as a pilot phase (2005–2007) and after a second trading period (2008–2012) dominated by the economic crisis and relatively low prices for EU allowances (EUAs), the EU ETS has further matured during the third trading period (2013–2020).

The EUA price has recently recovered, and has climbed above 50 Euro/tCO_2 in the Spring of 2021. Reasons for this price increase include changes in regulation, such as the introduction of the market stability reserve in 2019,[1] and the EU's raised ambitions on reducing greenhouse gas emissions to at least 55% below 1990 levels by 2030. This target is expected to set the EU on a path of becoming climate neutral by 2050. To this end, the emission target for the EU ETS will also have to become more ambitious. In addition, the EU is currently considering extending the scope of the EU ETS to include additional sectors such as maritime transport and possibly heating and transportation. It is therefore expected that the EU ETS will become even more instrumental to achieving future EU climate targets.

Emissions trading is considered an environmental policy instrument that achieves a given emissions target at minimum cost. Assuming that companies which are covered by an ETS bid for allowances at their marginal abatement costs, the price of emission allowances correctly signals scarcity in the allowance market (Montgomery 1972; Hahn and Stavins 2011). This efficiency result critically hinges on companies' willingness and ability to trade allowances. At least two factors might discourage companies from trading allowances, thereby reducing the efficiency of emissions trading. First, transaction costs discourage allowance trading and therefore increase total compliance costs (Stavins 1995).

[1] The market stability reserve regulates the supply and demand of allowances depending on the number of allowances in circulation. It is expected to reduce the supply of allowances by at least 2000 million EUAs by 2023 (e.g. Bocklet et al. 2019) and to affect the time profile of low-carbon investments (Perino and Willner 2019).

Second, companies may not correctly evaluate the opportunity cost of holding allowances. Consider a situation in which companies are allocated amounts that equal their emissions and thus that compliance is possible without further trading. The efficiency gains in emissions trading will be realized only if companies correctly evaluate the opportunity costs of holding allowances against the market price. By bidding marginal abatement costs into the market, companies could realize gains by reallocating allowances according to their costs. These two factors illustrate that understanding why and how companies trade allowances is critical for evaluating the performance of allowance markets and for improving the future design of emissions-trading systems.

In this paper, we ask how the characteristics of individual companies and institutional features of the emissions-trading system influence companies' trading behaviour. We empirically explore these factors in the context of the EU ETS for the years 2005 through 2014, i.e. the first ten years after the EU ETS came into force. To this end, we compile a large panel dataset of transactions in the EU ETS, allocations of allowances, and verified emissions from the EU transaction log (EUTL). We also include company characteristics from the ORBIS database. We relate companies' transactions to their characteristics, including size, number of installations, productivity, sector of operations, and net position (i.e. an allowance allocation minus verified emissions). To measure market participation, we construct several indicators, including the amount and number of transactions as well as the usage of intermediaries and derivatives markets. We then employ panel econometric methods to analyse the impact of companies' characteristics on market participation by companies. Because companies have gained experience and the administrative rules of the EU ETS have changed over time, we analyse trading behaviour jointly for all periods as well as separately for the first, second, and the first two years of the third trading period. Moreover, we separately estimate the impact of allowance positions, i.e. whether companies can be considered net sellers or buyers, on their trading behaviour.

We find that trading behaviour is related to a company's size, its net position, its sector affiliation, productivity, and location. Larger companies, those with higher (absolute) net positions, those operating in the energy or carbon leakage sectors (compared with non-carbon-leakage industries) and those with higher productivity are typically more likely to participate in the market and also to use the market more intensively. Considering differences across the three trading periods, we find that companies were generally more active in the second and third trading periods than in the first trading period. Finally, our results suggest that net buyers are more likely to participate in emissions trading and to trade higher volumes than net sellers. If the primary allocation of allowances impacts allowance positions, this asymmetry in trading behaviour possibly reflects a violation of the Coase (1960) independence property.

Several authors have analysed the transaction behaviour of companies regulated under the EU ETS. Zaklan (2013) analyses the determinants of participation in emissions trading in the pilot phase of the EU ETS. Likewise, Jaraitė-Kažukauskė and Kažukauskas (2015) analyse trading behaviour using an explicit notion of transaction costs. Exploring the gains and losses involved in allowances trading, Cludius (2018) also notes forgone trading opportunities, in particular for small companies. Exploiting price differences between EUAs and allowances from international offset markets (CERs, ERUs) in the second trading period of the EU ETS, Naegele (2018) also estimates substantial (fixed) transaction costs related to allowance trading under the EU ETS. Hintermann and Ludwig (2019) find evidence of effects on transaction costs when trading allowances across country borders. Zaklan (2020) also concentrates on the second trading period and concludes that the method of primary allocation of allowances only weakly impacts abatement behaviour of electricity companies.[2] Relying on data for the first and second trading periods, Guo et al. (2020) find a positive correlation between profits from trading and abatement. Baudry et al. (2021) use a theoretical approach and data for the second trading period and find significant fixed and variable trading transaction costs. In addition to econometric approaches, network-based methods (Borghesi and Flori 2018; Karpf et al. 2018) and cluster analysis (Betz and Schmidt 2015) have also been used to study trading behaviour and trading patterns in the EU ETS.

Empirical evidence suggests that factors that explain whether a company trades EUAs in the market (i.e. decides to participate), also explain the level of participation (i.e. trade intensity). Larger companies, companies with more installations, and energy-sector companies are more likely to participate and more likely to trade intensively. Furthermore, a company's net position affects both participation and intensity decisions. Generally, a shortfall in allowances and the possibility of incurring a penalty seem to increase participation. Finally, company trading behaviour depends on ownership structure and the country or region in which a company is located.

Our analysis contributes to the existing literature in four major ways. First, existing studies analyse a single trading period, often the first and partly the second trading period.[3] We therefore add to the literature by extending that temporal scope to include parts of the third trading period through the year 2014 and by analysing each period separately as well as jointly. Our study therefore provides insights into whether findings from the early phase of the EU ETS also hold in later years, when the market is more mature and participants are more experienced. Furthermore, regulation of the EU ETS has changed over time. In particular, banking of EUAs into subsequent trading periods was allowed from the second trading periods onwards only. Thus, net sellers could decide to bank rather than sell excess allowances on the market before the end of the trading period. Moreover, the length of the trading periods has increased over time, providing companies with more flexibility to borrow allowances across years. In addition, from 2013 onwards, the share of auctioning increased substantially. Most notably, since 2013 companies in the power sector no longer receive EUAs for free (with some exceptions for generators located in Central and Eastern European countries). As a consequence, many companies were forced to rely on auctions and the market more intensively to be in compliance. Last but not least, the price of EUAs and hence the incentives for companies to use emissions trading efficiently varied over time. Despite the economic crisis, average EUA prices were higher in the second trading period than in the first trading period and at the beginning of the third period.

Second, previous analyses focus on participation and total trading volume as key indicators. In this analysis, we also consider the number of transactions, the use of market intermediaries such as brokers, banks and exchanges, and the use of forwards and futures markets. Thus, our set of indicators is more comprehensive and likely to capture not only search- and information-related transaction costs but also costs pertaining to managerial competencies. The EU ETS involves uncertainties about the fundamentals driving the market (including uncertainty about regulations). Employing brokers and other intermediaries, companies gain access to professional market information (after paying brokerage fees). Similarly, companies may employ intermediaries to manage their trading activities directly,

[2] Based on interviews with managers in the ceramics industry, however, Venmans (2016) concludes that companies which are short tend to abate more.

[3] In another context, however, Hintermann and Ludwig (2019) and Naegele (2018) use data through 2013 and 2012, respectively.

broker trades with other system participants, use them as partners when entering into forwards or futures trading, or help them exploit opportunities to generate revenues, such as swapping cheaper international credits (CERs, ERUs) for more expensive EUAs (Cludius and Betz 2020). Financial products on the derivatives market enable companies to exploit price variations over time and manage market risks.

Third, our study emphasises asymmetric trading behaviour. We analyse how trading behaviour depends on companies' net positions, i.e. whether companies are net sellers or buyers. If companies' behaviour depends on their net positions, this is a strong indication of a failure of Coase's (1960) independence property, implying that the trading behaviour is independent of the method of primary allocation of allowances. We therefore add to the scarce empirical literature (Venmans, 2016; Zaklan 2020) on the independence of allowance allocation by analysing trading behaviour that varies with allowance positions.

Fourth, we employ a dataset which facilitates an analysis at the company level. Related studies have analysed transactions at either the level of individual installations (Betz and Schmidt 2015), the level of the national ultimate owner (Jaraitė-Kažukauskė and Kažukauskas 2015), or the level of the global ultimate owner (Cludius 2018; Hintermann and Ludwig 2019; Naegele 2018; Zaklan 2013).[4] We analyse transaction behaviour at the level closest to the point of regulation but not at the installation level. Operators of individual installations are unlikely to be responsible for making these decisions, as they might lack relevant expertise. Indeed, Betz and Schmidt (2015) observe that many companies pool EUAs for all their installations into one account. Because of language barriers, coordination and other types of transaction costs, the global ultimate owner is unlikely to be in charge of trading EUAs. We therefore believe that trading decisions are typically made at the level of the company or the national ultimate owner. For the purpose of this paper, we choose the company level because decisions at the company level also reflect decisions by the national ultimate owner, but not vice versa.

The remainder of our paper is organized as follows. In Sect. 2 we describe the methodology, including the dataset, the dependent and explanatory variables, and the econometric methods. Results are presented in Sect. 3. The final Sect. 4 summarizes the main findings and concludes.

2 Methodology

In this section, we first document how we assembled our data set. Then we report the dependent and explanatory variables used in the econometric analysis. Finally, we describe the econometric methods used.

2.1 Data

Our research is based on EUTL data, which can be downloaded free of charge from the European Commission's website, where the data on transactions are published with a

[4] For multi-national companies, the national ultimate owner is the subsidiary that owns all other subsidiaries in a given country. In contrast, the global ultimate owner is the global parent company that ultimately owns all subsidiaries (usually by controlling the national ultimate owners). We refer to a company as the legal organization that operates closest to the regulated entity, i.e. the installation.

three-year delay. The data used are organized into three datasets: (i) the main dataset containing all transactions completed in the EU ETS[5]; (ii) account data, which contain information pertaining to the accounts involved in transactions, such as account owners; and (iii) installation data, which provide information pertaining to free allocations and compliance per regulated installation. In addition, company information such as turnover, number of employees, and industry sector was taken from the ORBIS database of the Bureau van Dijk. We matched the EUTL data to the ORBIS data using company registration numbers. In cases where a match with a registration number was not feasible, we matched the account names and addresses of the account holders to the ORBIS database.[6] For the sake of analysis, we aggregate transactions on an annual per-company basis. In doing so, we exclude administrative transactions such as primary allocations and surrenders of allowances. These transactions account for about 65% of the transaction volume, but they do not reflect trading activity. Following Cludius and Betz (2020), a (trading) year in our dataset is defined as running from May through April because the surrender of allowances for an observation year usually takes place in April of the following year. Our observation period thus uses observations between January 2005 and April 2015, which means that our analyses cover two full years of the third trading period.

We only include regulated stationary installations and respective companies in our econometric analysis. We thus exclude aircraft operators as well as all observations where both verified emissions and allocations were zero, thus ensuring that only EU ETS–regulated companies remain in the dataset and that plants that have ceased operations but are still listed in the EUTL were excluded. We further removed all transactions between accounts of the same installation because we consider these trades to take place for organizational purposes only. In comparison, we do not remove intra-company trades. "Appendix 1" provides a more detailed description of how we compiled the data.[7]

2.2 Variables

2.2.1 Dependent Variables

Our empirical analysis considers four indicators that reflect participation in emissions trading, as shown in Table 1. We employ *total transactions* as measured by the volume

[5] Trades of international offsets like certified emission reductions (CERs) and emission reduction units (ERUs) are included in the dataset as long as they take place within the EUTL registry. If an account registered within the EUTL acquires or transfers an offset certificate from a party not registered in the EUTL, the counterparty is usually not known. If both parties are registered in the EUTL, the transaction is treated like a normal transfer. For the period between 2008 and 2012 we are, in principle, able to identify the type of transferred units. Since 2013, this information is, however, no longer observable as offsets are converted into EUAs when imported into the system (banked offsets had to be converted as well).

[6] This procedure extends work in previous studies (e.g. Jaraitė-Kažukauskė and Kažukauskas 2015; Hintermann and Ludwig 2019; Zaklan 2013) by using company registration numbers in addition to addresses and account names to match these datasets. This was possible after reporting of company registration numbers became mandatory in 2012.

[7] We do not correct the data for carousel VAT tax fraud, which was particularly relevant in the second trading period (e.g. Frunza et al. 2011). However, since we cannot clearly identify trades for tax fraud purposes in the data, we decided not to correct our data. Because our analysis includes accounts only of companies with at least one regulated installation and where information in the ORBIS database was available, most of the fraud-related transactions should be excluded. Fraud-related transactions were typically carried out via private accounts owned by shell companies which were not related to a company covered by the EU ETS.

Table 1 Description of dependent variables and covariates

Variable	Description	Data base
Dependent variables		
Total transactions	Transaction volume of EUA in trading year t (in metric tons of CO_2eq.)	EUTL
Transaction frequency	Number of transactions in trading year t	EUTL
Use of intermediaries	Number of intermediaries used in trading year t	EUTL/ORBIS
Use of forwards and futures	Estimated transactions involving EUA via forwards and futures (in metric tons of CO_2eq.)	EUTL
Explanatory variables		
Net position	Allocation of EUA minus verified emissions in year t (absolute value in metric tons of CO_2eq.)	EUTL
Carbon leakage	Dummy = 1, if company belongs to carbon leakage sector	ORBIS
Energy	Dummy = 1, if company belongs to energy sector according to NACE (rev2) classification (35.00 to 35.30)	ORBIS
Productivity	Calculated as revenues divided by number of employees in year t (in 100.000 Euro/employee)	ORBIS
Employees	Number of employees	ORBIS
Installations	Number of installations	EUTL
Period	Dummy for each trading period (base period is the first trading period)	EUTL
Region 1	Austria (AT), Germany (DE), Liechtenstein (LI)	EUTL
Region 2	Belgium (BE), France (FR), Netherlands (NL)	EUTL
Region 3	Greece (GR), Cyprus (CY), Spain (ES), Italy (IT), Malta (MT), Portugal (PT)	EUTL
Region 4	Estonia (EE), Lithuania (LT), Latvia (LV), Poland (PL)	EUTL
Region 5	Czech Republic (CZ), Hungary (HU), Slovenia (SI), Slovakia (SK)	EUTL
Region 6	Denmark (DK), Finland (FI), Iceland (IS), Norway (NO), Sweden (SE)	EUTL
Region 7	United Kingdom (UK), Ireland (IE)	EUTL
Region 8	Bulgaria (BG), Croatia (HR), Romania (RO)	EUTL

of allowances transacted via purchases or sales per trading year. We also use *transaction frequency* as measured by the number of transactions a company carries out per year. A higher *transaction frequency* is assumed to reflect stronger participation in emissions trading. Further, we consider the *use of intermediaries* by a company to carry out its trades. To determine the number of intermediaries used, we identified those trading partners of a regulated entity that belong to the NACE financial services category. Finally, companies may use financial products that are available on the derivatives market to exploit price variations over time and manage market risks. We therefore consider the *use of forwards and futures* as reflecting a company's greater use of the EU ETS. Because only actual allowance transactions are registered in the EUTL, the volume of transactions that was carried out via forwards and futures contracts has to be estimated. We define the volume traded via forwards and futures as transactions that a company carried out on days when forwards or futures were typically delivered (see Cludius 2018). These days were determined by looking at trading activities in the so-called clearing accounts.[8]

2.2.2 Explanatory Variables

Our choice of explanatory variables (see also Table 1; "Appendix 2, Table 3" reports the descriptive statistics) is guided by the existing literature and the availability of data. To account for companies' incentives to participate in the market we include the *net position*, which we define as the absolute value of the difference between the number of allowances allocated for free and verified emissions per year. Hence, *net position* takes nonnegative values and corresponds to a net deficit for buyers and a net surplus for sellers.[9]

Companies with a higher net surplus need to buy relatively fewer allowances or they can sell more allowances on the market to achieve compliance. Similarly, companies with larger net deficits must purchase more allowances (or further reduce emissions) to be in compliance. The existing literature finds companies' net surplus to be related to market participation and transaction volume (Cludius 2018, Jaraitė-Kažukauskė and Kažukauskas 2015, Martin et al. 2015, Naegele 2018, and Zaklan 2013). We therefore expect companies with higher net surpluses or with higher net deficits to use forwards and futures more intensively. As in Jaraitė-Kažukauskė and Kažukauskas (2015) and Zaklan (2013), our

[8] EUA futures are traded at regulated marketplaces (e.g. at the European Energy Exchange, Intercontinental Exchange). Participants must be registered, e.g. at the London Clearing House. The clearing accounts show heightened activity during a few days in December each year when futures are typically delivered. For our analysis, the following days showed significantly higher trade volumes (at least three times as high as on normal days) and are therefore selected to calculate the use of futures: 21–23/12 2005, 18–22/12 2006, 17–19/12 2007, 15–19/12 2008, 14–18/12 2009, 20–23/12 2010, 20–23/12 2011, 17–21/12 2012, 17–20/12 23/12 2013, 16–19/12 22–23/12 2014.

Forwards are traded bilaterally and not necessarily cleared. Delivery usually takes place during the last business day in November or the first business day in December. For our analysis, these days are: 30/11 01/12 2005, 30/11 01/12 2006, 30/11 03/12 2007, 28/11 01/12 2008, 30/11 01/12 2009, 30/11 01/12 2010, 30/11 01/12 2011, 30/11 03/12 2012, 29/11 02/12 2013, 28/11 01/12 2014.

[9] This definition follows the literature (e.g. Jaraitė-Kažukauskė and Kažukauskas, 2015; Zaklan 2013) but abstracts from the fact that a company's verified emissions may depend on trading (versus abatement) activities and does not include banked allowances. As explained in "Appendix Compiling of the data", due to inconsistencies in the data, we did not include information from the EUTL pertaining to banked allowances. Accounting for banked allowances would increase the value of *net position*, because companies which are short (or long) in year t are likely to have been short (or long) in year t-1. Because borrowing, unlike banking, is not allowed across trading periods, accounting for banking would asymmetrically affect the net positions of net buyers and net sellers.

definitions of ‘net surplus’ and ‘net deficit’ do not account for EUAs which were banked from previous years or borrowed from subsequent years.

To capture the effects of sector affiliation, our set of explanatory variables includes two dummy variables. First, *carbon leakage* identifies companies belonging to a sector which is categorized as being at risk of carbon leakage under EU ETS rules.[10] Because they face import competition, these companies likely cannot fully pass on the additional CO_2 costs to their customers without losing market share (Cludius 2020). Therefore, these companies are expected to have stronger incentives to use emissions trading to minimize compliance costs. Previous studies have not accounted for effects specific to companies operating in carbon-leakage sectors.

Second, *energy* denotes companies in the energy sector. These companies are often experienced traders of energy products. In particular, electricity generators typically sell electricity on spot and futures markets. Often, these products are traded at the same exchange as allowances (e.g. the European Energy Exchange—EEX). Hence, trading-related transaction costs should be lower and participation in emissions trading higher than for most non-energy companies. The findings for the sector dummies need to be interpreted by reference to the base category which comprises companies belonging to non-leakage industry sectors and organizations from sectors that operate combustion plants with more than 20 MW of nominal capacity (e.g. a university or large hospital operating a power plant). For the sake of brevity, we refer to this base category as the non-leakage industry sector.

Our explanatory variables also include *productivity* which is calculated as a company’s revenues per employee. We expect that a company which enjoys higher per-capita revenues is also more likely to make greater use of emissions trading. To capture the effects of size on the use of emissions trading, our explanatory variables also include the number of *employees*. We also include the *number of installations*. Following Jaraitė-Kažukauskė and Kažukauskas (2015), we expect companies that operate more installations to be more active in emissions trading because they are believed to incur lower search and information costs.

Further, to capture differences across trading periods we include a separate dummy for our trading periods (using the first trading period as the base period). Similarly, we control for region-specific effects by including a dummy variable for the regions. Region 1, which consists of the German-speaking countries (not including Switzerland and Luxembourg) is used as the base category. For the econometric estimations, we use the natural logarithms of *total transactions*, *use of forwards and futures, net position, productivity,* and *employees.*

2.3 Econometric Models

We employ panel econometric models to exploit the (unbalanced) panel structure of our data.[11] In particular, we run various types of econometric models to adequately reflect the nature of the dependent variables.

[10] The carbon-leakage list includes a large number of products from various industry sectors. In our case, these sectors include: refineries, iron and steel, metals, aluminium, cement and lime, glass and ceramics, pulp and paper, and chemicals as well as food, textiles, and machinery production.

[11] The panel is unbalanced because of exit and entry of companies and installations, and because countries joined the EU ETS at different points in time. In particular, the three non-EU members, Norway, Iceland, and Liechtenstein as well as Romania and Bulgaria joined the system in 2007 and Croatia in 2013.

2.3.1 Double Hurdle Model

First, for *total transactions* and *use of forwards and futures*, our econometric models reflect the fact that, for a substantial portion of observations, the outcome is zero. More specifically, the share of zeros is about 44% for *total transactions* and 90% for the *use of forwards and futures* for the final samples in the multivariate analyses. These zeroes reflect company-level decisions to not participate in the market, for example, or to not trade in forwards and futures. In this case, running ordinary least squares models would result in biased parameter estimates. Following Jaraitė-Kažukauskė and Kažukauskas (2015), we therefore employ so-called "double-hurdle" panel models, which explicitly model the "participation decision" (first hurdle), i.e. whether companies decide to participate in the market at all, and the "intensity decision" (second hurdle), i.e. the extent to which companies use the market. Following the seminal work by Cragg (1971), the participation decision is essentially modelled as a Probit model and the intensity equation is modelled as a Tobit (corner solution) model. Double-hurdle models are preferable to standard Tobit models because the latter involve more restrictive distributional assumptions. For example, in Tobit models, the sign of the coefficient associated with a particular variable must be the same in both equations.

Formally, we model the "participation decision" (first hurdle) in our "double hurdle" as

$$D_{it} = \begin{cases} 1 & if\, D^*_{it} > 0 \\ 0 & otherwise \end{cases} \tag{1}$$

$$D^*_{it} = x_{it}\boldsymbol{\beta} + z_i\boldsymbol{\gamma} + \alpha_{1,i} + \varepsilon_{1,it} \tag{2}$$

where D_{it} is an indicator variable capturing whether company i participates in an emissions trading activity at time t or not. D^*_{it} is a latent (unobserved) variable reflecting company i's net benefits derived from an emissions trading activity such as buying and selling EUAs. x_{it} is a vector of time-varying explanatory variables such as verified emissions. z_i is a vector of time-invariant explanatory variables such as sector affiliation. $\alpha_{1,i}$ denotes time-invariant company-specific unobservable factors such as company culture and $\varepsilon_{1,it}$ is an idiosyncratic error term with $\varepsilon_{1,it} \sim N(0,1)$. Double-hurdle models are nonlinear models. Therefore, unlike with linear models, unobserved time-constant heterogeneity (e.g. company culture), which may be correlated with the covariates, cannot be managed by including company-specific fixed effects in the model and then employing a fixed-effects estimator. On the other hand, using a random effects estimator requires unobserved heterogeneity to be uncorrelated with the covariates. This assumption is likely to be restrictive in our context. We therefore employ the correlated random-effects estimator (CRE) developed by Mundlak (1978). To control for time-invariant unobserved heterogeneity, the CRE includes the company-specific means of the time-varying variables in the regression equations. Thus,

$$\alpha_{1,i} = \bar{x}_i\boldsymbol{\varphi} + \mu_i \tag{3}$$

where $\overline{x}_i$ is the mean of the x_{it} over time for company i, and $\mu_i \sim N\left(0, \sigma_\mu^2\right)$.[12] The (conditional) probability that a company passes the first hurdle, i.e. participates in an emissions trading activity, is then

$$\Pr\left(D_{it} = 1 | x_{it}, z_i, \overline{x}_i, \mu_{i;} \boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\varphi}\right) = \Phi\left(x_{it}\boldsymbol{\beta} + z_i\boldsymbol{\gamma} + \overline{x}_i\boldsymbol{\varphi} + \mu_i + \varepsilon_{1,it}\right) \tag{4}$$

where $\Phi(.)$ denotes the cumulative density function of the standard normal distribution.

We model the "intensity decision" (second hurdle) as

$$Y_{it}^{*} = \max\left(Y_{it}^{**}, 0\right) \tag{5}$$

$$Y_{it}^{**} = x_{it}\boldsymbol{\delta} + z_i\boldsymbol{\theta} + \alpha_{2,i} + \varepsilon_{2,it} \tag{6}$$

where Y_{it}^{**} indicates company i's desired level of the emissions trading activity at time t, $\alpha_{2,i}$ captures time-invariant company-specific unobservable factors, and $\varepsilon_{2,it}$ is an idiosyncratic error term with $\varepsilon_{2,it} \sim N\left(0, \sigma_{\varepsilon 2}^2\right)$. For the intensity decision, we model unobserved company-specific heterogeneity similar to Eq. (3). Combining both hurdles, the observed level of emissions trading activity of company i at time t is then

$$Y_{it} = D_{it}Y_{it}^{*} \tag{7}$$

Finally, our empirical specification of the double-hurdle model allows for non-zero correlation between the participation and intensity equations. We estimate the panel double-hurdle model using the *bootdhreg* command developed by Engel and Moffatt (2014) for Stata, which provides bootstrapped standard errors.

2.3.2 Poisson Model

To reflect the count nature of the dependent variables, *transaction frequency* and *use of intermediaries*, we estimate panel Poisson models. These models rely on equi-dispersion, i.e. the conditional mean is assumed to be equal to the conditional variance. Negative binomial models, for example, do not hinge on this assumption. Because they involve less restrictive distributional assumptions, however, we chose Poisson panel models as our preferred method for estimating the count data models.

Formally, the Poisson model assumes that the dependent variable (y_{it}), e.g. the number of transactions j carried out by company i during time t, follows a Poisson distribution. We specify the conditional probability of observing j as

$$\Pr\left(y_{it} = j | x_{it},\ z_i,\ \alpha_{3,i}; \boldsymbol{\zeta}, \boldsymbol{\pi}\right) = \frac{\left[\exp\left(-\lambda_{it}\right)\right]\left(\lambda_{it}\right)^{y_{it}}}{y_{it}!} \quad \text{for } j = 0, 1, 2, \ldots \tag{8}$$

where λ_{it} denotes the conditional mean and the conditional variance of y_{it} and is modelled as

[12] The $\overline{x}_i$ are referred to as Mundlak terms. They pick up the "between variation" and may be interpreted as the long-run effects. In comparison, the time-varying variables pick up the "within variation" and may be interpreted as the short-run effects. Because we worry, that the effects of unobserved heterogeneity may be correlated with the explanatory variables, our presentation and interpretation of the results will focus on the time-varying effects.

$$\lambda_{it} = \exp\left(x_{it}\boldsymbol{\zeta} + z_i\boldsymbol{\pi} + \alpha_{3,i}\right) \tag{9}$$

Similar to Eqs. (2) and (6) in the double hurdle model, $\alpha_{3,i}$ captures time-invariant company-specific unobservable factors in the Poisson model. Likewise, we model unobserved company-specific heterogeneity as in Eq. (3). We estimate our CRE Poisson model via conditional maximum likelihood methods as implemented in Stata.

3 Results

We first present and discuss the results for the entire 2005–2014 period. We then summarize the findings of the analysis pertaining to the individual trading periods. Finally, we summarize the results obtained when distinguishing between net sellers and net buyers of allowances.

3.1 Results for the Full Period (2005–2014)

We present findings for our four indicators in Table 2. Robust standard errors are clustered at the company level and reported in parentheses below the parameter estimates. The final sample includes observations for 6316 companies.

First, we note that the results for the Mundlak terms suggest that employing a pure random-effects estimator would lead to biased and inconsistent parameter estimates for all four models. In addition, for the two double-hurdle models, the coefficients associated with the Mills ratio are statistically significant, suggesting that imposing a zero covariance when estimating the participation and intensity equations would also result in biased and inconsistent parameter estimates. We turn now to the individual findings for the four indicators.

3.1.1 Total Transactions

The first set of results reported in Table 2 represent the findings from estimating a double-hurdle model, where the first hurdle captures participation, i.e. whether a company buys or sells EUAs in a particular year or not. For those companies, the second hurdle captures the transaction intensity, i.e. the transaction volume. The results presented in Table 2 imply that a company that has a higher *net position*, is on the *carbon leakage* list, operates in the *energy sector* (as opposed to a non-carbon-leakage industries sector), enjoys higher *productivity*, has more *employees*, or operates more *installations* is more likely to participate in emissions trading and, conditional on participation, to also transact in larger volumes. Calculating the average marginal effects for the participation equation, we find that a 1% increase in the net position increases the probability of participating in emissions trading by on average 3.9 percentage points (see "Appendix 3, Table 6"). Similarly, operating in the *energy* sector (rather than in the non-carbon-leakage industries sector) increases the probability of participation by 6.3 percentage points. For the intensity equation, the coefficients presented in Table 2 reflect the marginal effects (or discrete probability effects for dummy variables) conditional on participation. Thus, a 1% increase in a company's net position increases the volume of transactions on average by about 0.37% (using the point

Table 2 Results for 2005–2014

	Total transactions		Transaction frequency	Use of intermediaries	Use of forwards and futures	
	Participation	Intensity			Participation	Intensity
Net position	0.101*** (0.008)	0.373*** (0.025)	0.112*** (0.013)	0.108*** (0.014)	0.076*** (0.012)	0.520*** (0.084)
Carbon leakage	0.103*** (0.021)	0.221*** (0.044)	0.135*** (0.036)	0.203*** (0.062)	0.101*** (0.040)	0.475*** (0.156)
Energy	0.218*** (0.032)	0.361*** (0.064)	0.340*** (0.067)	0.193** (0.096)	0.270*** (0.060)	1.717*** (0.352)
Productivity	0.194*** (0.032)	0.135*** (0.032)	0.075 (0.057)	0.078* (0.043)	0.030 (0.027)	0.313*** (0.089)
Employees	0.110*** (0.028)	0.109*** (0.030)	0.132*** (0.048)	0.062 (0.050)	0.026 (0.031)	0.286*** (0.112)
Installations	0.067*** (0.015)	0.051*** (0.008)	0.177*** (0.014)	0.023*** (0.008)	0.012*** (0.005)	0.040*** (0.013)
Period 2	0.468*** (0.017)	0.839*** (0.068)	0.568*** (0.041)	1.069*** (0.048)	−0.034 (0.027)	3.146*** (0.575)
Period 3	0.462*** (0.021)	0.535*** (0.066)	0.332*** (0.055)	0.839*** (0.055)	0.015 (0.029)	1.123*** (0.195)
Region 2 (BE, FR, NL)	−0.216*** (0.038)	−0.191*** (0.072)	−0.017 (0.160)	−0.589*** (0.208)	−0.259*** (0.046)	−1.512*** (0.356)
Region 3 (GR, IT, PT, ES, CY, MT)	0.019 (0.032)	−0.186*** (0.047)	0.047 (0.068)	−0.186* (0.104)	−0.275*** (0.045)	−1.955*** (0.356)
Region 4 (EE, LT, LV, PL)	−0.343*** (0.040)	−0.179** (0.083)	−0.206*** (0.076)	−0.354*** (0.109)	−0.513*** (0.067)	−2.589*** (0.607)
Region 5 (CZ, HU, SI, SK)	−0.040 (0.036)	−0.182*** (0.072)	−0.063 (0.066)	0.409*** (0.089)	−0.432*** (0.056)	−2.355*** (0.515)
Region 6 (DK, FI, IS, NO, SE)	0.299*** (0.047)	−0.401*** (0.075)	0.239** (0.105)	−0.844*** (0.159)	−0.076* (0.053)	−0.842*** (0.151)
Region 7 (UK, IE)	−0.044 (0.048)	−0.245*** (0.077)	−0.133* (0.077)	−0.845*** (0.129)	−0.360*** (0.055)	−1.997*** (0.495)
Region 8 (BG, HR, RO)	−0.098** (0.053)	0.176*** (0.099)	−0.016 (0.092)	−0.100 (0.129)	−0.859*** (0.100)	−4.140*** (1.021)
Mills ratio		0.831*** (0.229)				6.202*** (1.381)
Mean net position	0.106*** (0.009)	0.573*** (0.024)	0.129*** (0.030)	0.124*** (0.038)	0.527*** (0.028)	1.042*** (0.155)
Mean productivity	−0.212*** (0.033)	−0.022 (0.039)	0.024 (0.058)	−0.098* (0.055)	0.171*** (0.034)	−0.031 (0.093)
Mean employees	−0.134*** (0.030)	0.017 (0.033)	−0.0241 (0.051)	0.014 (0.058)	0.135*** (0.017)	0.182* (0.114)
Constant	−2.031 (0.064)	−0.748*** (0.416)	−3.164*** (0.096)	−4.856*** (0.162)	−3.753*** (0.095)	6.202*** (1.381)
Log likelihood	−56,332.57		−73,885.28	−17,160.12	−15,624.39	
χ^2 (Prob > χ^2)	33,701.99 (0.000)		6210.60 (0.000)	5873.94 (0.000)	3369.90 (0.000)	
Number of companies	6316		6316	6316	6316	
Number of observations	35,056		35,056	35,056	35,056	

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$

estimate reported in Table 2 and keeping in mind that *total transactions* and *net position* are specified in natural logarithm). Belonging to the *energy* sector (as opposed to a non-carbon leakage industries sector) increases the total transaction volume by about 36%.

The probability of participating in emissions trading and transaction intensity were higher in the second and third trading periods than in the first trading period. In most regions, participation and intensity were typically lower than in the German-speaking base region. The probability of participating in emissions trading was higher than in the base region only in the Nordic countries.

3.1.2 Transaction Frequency

The results for *transaction frequency* suggest that, on average, a company with a higher *net position* or which operates in a *carbon leakage* sector or the *energy* sector trades more frequently. Similarly, we find that larger companies (as measured by the number of *employees*) and companies with more *installations* trade more frequently. In comparison, we find no evidence that *productivity* is related to transaction frequency. Compared with its level in the first trading period, *transaction frequency* appears to have been higher in the second and third trading periods. The findings for the region dummies suggest that, compared with the German speaking countries, companies located in the Nordic countries trade more frequently while countries located in regions 4 and 7 trade less frequently.

For most explanatory variables, the size effects are rather substantial. For example, the point estimate associated with *energy* suggests that the mean *transaction frequency* associated with companies in the *energy* sector is about 40.5% (exp(0.340) = 1.405) higher than for companies operating in non-leakage industry sectors.

3.1.3 Use of Intermediaries

A company with a higher *net position* or a company operating in a *carbon leakage* sector or in the *energy* sector uses more intermediaries. More productive companies and companies with more *installations* also use more intermediaries. In comparison, we find no evidence that the size of a company (as measured by employees) is related to the *use of intermediaries*. We further find that the *use of intermediaries* increased in the second and third trading periods compared with the first trading period. There is also substantial heterogeneity in the *use of intermediaries* across regions. Except for region 5, companies in most regions use fewer intermediaries than companies in the German-speaking region.

Again, the size effects are relevant. Operating in a *carbon leakage* sector, for example, is estimated to increase the average number of intermediaries used by about 22.5% (exp(0.203) = 1.225) compared with companies in non-carbon leakage industries sectors.

3.1.4 Use of Forwards and Futures

Our findings for the *use of forwards and futures* imply that a company with a higher *net position* is more likely to participate in the derivatives market and, conditional on participation, to also trade forwards and futures in larger volumes. Calculating the average marginal effects, we find that an increase in the *net position* increases the probability of participating in the derivatives market by about 1.0 percentage points (see "Appendix 3,

Table 6”). The results further suggest, for example, that for a company trading on the derivatives market, a 1% increase in the net position increases the volume of EUAs traded on the derivatives market by about 0.52%. Further, we find that operating in a *carbon leakage* sector or the *energy* sector increases a company’s propensity to participate in the derivatives market and, conditional on participation, to trade in forwards and futures in higher volumes than companies operating in non-carbon-leakage industries sectors. For example, belonging to the *energy* sector increases the probability of participating in the derivatives market by about 2.2 percentage points. Both *productivity* and the number of *employees* appear to be positively related to the intensity of derivatives-market trading, but not with the decision to participate in this market. In comparison, companies with more *installations* are more likely to participate in the derivatives market and, conditional on participation, to trade at higher volumes of forwards and futures.

For the derivatives market, intensity of usage was stronger in the second and third trading periods than in the first trading period. Finally, participation and intensity were higher in the German-speaking region than in all other regions, ceteris paribus.

3.1.5 Discussion of Results

In general, the estimation results for our explanatory variables for 2005–2014 are consistent across the four indicators that reflect companies’ emissions-trading behaviour. More specifically, we find that the *net position* and operating in the *energy* sector increase emissions-trading activities in the EU ETS. In our double-hurdle models these variables are positively related with participation and, conditional on participation, with the volume of EUAs traded. These results are in line with the findings for the first trading period reported by Cludius (2018), Jaraitė-Kažukauskė and Kažukauskas (2015) and Zaklan (2013), who note the importance of net position and sector affiliation for companies’ trading activities. As an extension to previous studies, our research explicitly accounts for the effects of operating in a *carbon leakage* sector on emissions-trading activities (as compared with companies operating in non-leakage industry sectors or the energy sector). We find operating in a carbon-leakage sector to be positively related to all indicators reflecting emissions-trading behaviour. Jaraitė-Kažukauskė and Kažukauskas (2015) include sectoral dummies for several ETS industry sectors and find that they are generally less likely to be active than energy companies. They do not, however, link their activity to the carbon-leakage status of a particular sector.

We also find that, in general, the number of *employees*, which we use as a proxy for the size of a company, is positively related to companies’ emissions-trading activities (with the exception of the *use of intermediaries* and participation in the *use of forwards and futures*). Using the primary allocation to reflect company size, Jaraitė-Kažukauskė and Kažukauskas (2015) find for the first trading period that larger companies are more likely to participate in emissions trading. In addition, they find that company size (measured by fixed assets and total revenue) correlates positively with the intensity of inter-company trading of EUAs. For the second trading period, Baudry et al. (2021) find that larger companies (using the emissions volumes to proxy size) trade at higher volumes. Finally, Cludius and Betz (2020) conclude that larger companies (as measured by emissions volumes) are more likely to trade with a larger variety of intermediaries. Thus, our findings for size are generally in line with those reported in the existing literature, even though we employ a different proxy from those used in previous studies.

We further find that company *productivity* (i.e. revenues per employee) is typically positively related to our activity indicators (with the exception of *transaction frequency* and participation in *use of forwards and futures*). For the first trading period (and hence with a much smaller sample), Zaklan (2013) finds no evidence that a company's profitability (proxied as return on assets and as revenues compared with total assets) —which should be closely related to productivity—is associated with its trading activity.

We find the number of *installations* to be positively related to all four indicators of activity (including both participation and intensity of participation in *total transactions* as well as *use of forwards and futures*). These results speak directly to the findings by Jaraitė-Kažukauskė and Kažukauskas (2015), who conclude that trading-transaction costs existed in the introductory phase of the EU ETS. As evidence, they point to the positive relationship between intra-firm trading and the number of installations which are supposed to reflect search- and information-related costs. We find, similarly, that, for the entire study period of 2005–2014, the number of *installations* is positively related to market participation, the intensity of trading, and the *use of intermediaries*. Thus, following this line of argument, our findings for size and number of installations provide no evidence that trading-transaction costs have declined over time. Similarly, to findings reported by Jaraitė-Kažukauskė and Kažukauskas (2015), our results may suggest that transaction costs are characterized by economies of scale and—because they affect the intensity of transactions and forwards and futures—are composed of fixed and variable fractions.

The results for the region dummies indicate that a company's emissions-trading activities are related with its geographical location. For most regions, though, we found no clear patterns across the four indicators. The importance of the location of an installation or company for its trading behaviour has previously been noted in network analyses of the EU ETS (Borghesi and Flori 2018; Karpf et al. 2018). Likewise, Hintermann and Ludwig (2019) observe a "home bias" in companies' trading partner choices.

Finally, we observe that companies were generally more active in the second and third trading periods than in the first trading period. Transaction volume and trading frequency may have been particularly high in the second period as a result of the financial crisis. To increase liquidity, some companies sold their allowance allocations at the beginning of the trading year and later purchased the amount of allowances required for compliance just in time to meet the deadline (Cludius and Betz 2020). In the next section, we further explore differences between trading periods.

3.2 Results by Trading Period

To explore whether the effects of factors related to companies' emissions-trading activities have changed over time, we ran separate regressions for the three trading periods within the scope of the study. In this section, we briefly summarize our findings. We present the full estimation output in Tables 7, 8, and 9 of "Appendix 4". "Appendix 2, Table 4" reports the descriptive statistics for the dependent and explanatory variables by trading period.

In general, results for the individual trading periods are consistent with those presented for the entire 2005–2014 period of analysis in Table 2. This indicates that factors related to various emissions-trading activities remained stable over time. Yet, for some variables we observe differences across trading periods.

For companies participating in emissions trading we observe a stronger effect of *net position*, *carbon leakage* and *energy* on the intensity of *total transactions* in the second trading period than in the first and third trading periods. This finding may be explained by the higher average prices for EUAs in the second trading period compared with prices in the first trading period and compared with prices in 2013 and 2014.

For *transaction frequency,* we observe that the coefficient associated with *carbon leakage* is larger in the first trading period than in the second and third trading periods. This may be explained by the fact that carbon-leakage sectors such as cement and steel enjoyed particularly large surpluses of EUAs in the first trading period, which they eventually sold on the market, because banking of EUAs was not allowed between the first and the second trading periods. We further find *productivity* to be positively related to *transaction frequency* in the second trading period, while for the 2005–2014 period and for the first and third trading periods individually, this relationship is not statistically significant.

For *use of intermediaries*, the coefficient associated with *carbon leakage* is statistically significant for the second and third trading periods but not for the first trading period. Further, the effect of *energy* appears larger in the third trading period than in the first and second trading periods. We conjecture that this finding can be explained by the fact that since 2013 most companies in the power sector had to purchase virtually all the EUAs needed either at the auction or on the secondary market. To do so, they use market intermediaries more intensively. For example, EUTL data suggest that banks were the principal successful bidders at EUA auctions in 2013 and 2014.

For the *use of forwards and futures* we observe differences across periods mainly in the intensity equation. For example, findings reported in Table 9 suggest an increase in the coefficient associated with *net position* across trading periods. This finding might indicate that hedging becomes more relevant with tightening targets and the expectation of rising EUA prices. For *carbon leakage*, we find a statistically significant effect for the second trading period only, suggesting that the findings for 2005–2014 reported in Table 2 are driven predominantly by the activities taking place in this period. Most prominently, though, we observe a strong increase in the coefficient associated with *energy,* which again could be explained by the fact that in the third trading period the power sector no longer receives allowances for free but has to actively hedge its position on the secondary market.

We briefly turn to the variables that previous literature has assumed to capture transaction costs. For *employees*, we find some differences across trading periods. In particular, for *total transactions*, *transaction frequency*, and *use of intermediaries*, *employees* is statistically significant in in the first and second trading periods, but not in the third trading period. For *use of forwards and futures*, *employees* is found to be statistically significant for the participation decision in the first trading period only. In comparison, we find no strong evidence that the effects of the number of *installations* have weakened across trading periods. Thus, our findings provide mixed evidence that transaction costs have decreased over time.

3.3 Results for Total Transactions with Asymmetric Response for Net Sellers and Net Buyers

To explore whether the direction of the net position, i.e. whether a company's being "short" or "long" affects market participation and the intensity of transactions, we estimate a model which allows for an asymmetric response of net sellers and net buyers in the *total transactions* model. Net buyers (net sellers) are defined as companies where in a particular year the amount of free allocation is below (exceeds) verified emissions. Depending on its net position, a company may be classified as a net seller in one year and a net buyer in another year.

In theory, without market frictions, the opportunity costs of holding allowances should be the same for net buyers and net sellers. Thus, for a given net position, participation and trading intensity should not depend on whether companies are net sellers or net buyers. To explore this hypothesis for the data at hand, we include an interaction term to represent the relationship between net position and a dummy for net sellers as an additional explanatory variable. We present the results derived from estimating the double-hurdle model for *total transactions* for 2005–2014 in "Appendix 5, Table 10" and the results for the individual trading periods in Table 11. "Appendix 2, Table 5" reports the descriptive statistics for the dependent and explanatory variables for net buyers and net sellers.

We first note that the findings for the other explanatory variables are virtually identical to those presented for 2005–2014 in Table 2 and for the individual trading periods in Table 7. In particular, though, we find that the coefficient associated with the interaction term is negative and statistically significant for the participation equation in all samples and for the intensity equation in all samples except for the third period sample. Thus, for a given net position, net buyers are more likely to participate in emissions trading and—conditional on participation—to trade at higher volumes than net sellers. This finding supports the view that the actual or perceived opportunity costs of holding allowances differ between net sellers and net buyers. This asymmetry possibly reflects a violation of Coase's (1960) independence property. Depending on the initial allocation of allowances, some companies might build long positions. Our results then imply that these companies trade less intensively, distorting the market result.

Perhaps, this asymmetry can be explained by citing net buyers' intentions to avoid non-compliance and penalties. In addition, building on Kahneman and Tversky (1979) and Kahneman et al. (1990), company decision makers may perceive their endowment of free allocation as a reference point. If they value losses against this references point stronger than gains of equal size, their willingness to pay for allowances is lower than their willingness to accept for selling allowances. As a consequence, opportunity costs differ between buyers and sellers. Moreover, accounting rules which require "short" companies to itemize the value of missing allowances in their accounting statements (Ellerman et al., 2010) may further contribute to this asymmetry.

In addition, we observe differences across trading periods, suggesting that this asymmetry in opportunity costs between net sellers and net buyers has declined over time. This finding might be explained by institutional changes such as longer trading periods providing companies with more flexibility to borrow allowances across years or the emergence of market intermediaries and derivatives markets. In addition, companies are likely to have learned through experience with the EU ETS over time, improving their capacity to assess the opportunity costs of holding allowances.[13]

[13] In general, the EU ETS allows banking of allowances across trading periods and years, but not borrowing across periods. For the first trading period, neither banking nor borrowing was possible across periods. Because allowances for the year t + 1 are allocated before companies need to surrender allowances for emissions for year t, borrowing is de facto feasible also across years within the same trading period. Thus, the period pertaining to banking of allowances is longer than the period for borrowing.

3.4 Robustness Checks

To assess the robustness of the findings presented in Table 2 we carried out a series of additional analyses. These analyses allowed for alternative distributional assumptions and model specifications.

3.4.1 Distributional Assumptions

Rather than employing CRE Poisson models to estimate the regression equations for *transaction frequency* and *use of intermediaries*, we also estimate those using CRE negative binomial models. Compared with the Poisson model, the conditional probability function of the negative binomial model includes an additional term reflecting unobserved heterogeneity, which is assumed to follow a gamma distribution. Thus, unlike standard Poisson models, negative binomial models do not assume equi-dispersion. For both the *transaction frequency* and *use of intermediaries* equations, the findings of the CRE negative binomial model are virtually identical to those reported in Table 2. We also estimated Poisson fixed-effects models. The findings for the time-varying variables are almost identical to those presented in Table 2.[14]

3.4.2 Model Specification

First, following the literature (e.g. Zaklan 2013; Jaraitė-Kažukauskė and Kažukauskas 2015), we also distinguish between net buyers and net sellers by splitting the sample accordingly. In Tables 12 and 13 in "Appendix 6" we report the findings for net buyers and net sellers. At a very general level, the results we obtain for these samples are consistent with those for the full sample presented in Table 2. Thus, qualitatively, the factors related to companies' emissions-trading activities do not appear to differ between net buyers and net sellers. Noticeable differences pertaining to our explanatory variables exist, for example, for *carbon leakage*, where the coefficient in the participation equation for *total transactions* and for the *use of forwards and futures* is statistically different only for net sellers (and the full sample). Possibly, these null results for net buyers may reflect lower statistical power. In some instances, we also observe differences in the size effects. For example, the effects of *carbon leakage* are typically larger for net sellers than for net buyers. In comparison, the effects of *energy* are typically larger for net buyers than for net sellers. Finally, for *transaction frequency* and *use of intermediaries*, the effects of *net position* appear larger for net sellers than for net buyers, but we observe no differences for the other indicators.

Second, our results are very consistent with those reported in Table 2 if we use profit (before taxes) rather than revenues per employee. Because information on profits is often lacking in the ORBIS data base, employing profits rather than productivity involves a loss of almost 30% of observations. Our preferred specification therefore employs *productivity*. Third, because the dependent variables and revenues are contemporaneous, this may cause an endogeneity problem. More active use of emissions trading may increase revenues. We therefore estimated all models using lagged values for *productivity*. Because data on revenues and employees were available also for 2014, lagging *productivity* by one year did not cause any loss of observations. The results for these models are virtually identical to those

[14] All findings that are not shown to save space are available from the authors upon request.

reported in Table 2. Fourth, our preferred specification includes dummies for the three trading periods. To allow for a more fine-grained representation of temporal effects, we estimated the models using yearly dummies instead of trading-period dummies. The results for the explanatory variables are very similar to those shown in Table 2. Finally, to mitigate the effects of "outliers" at both ends of the distribution, we used ten categorical dummy variables reflecting the percentile of *net position*. For the Poisson models, the findings for the other explanatory variables are typically very similar to those displayed in Table 2. The double hurdle models, however, failed to achieve convergence.

4 Conclusions

The efficiency of any emissions-trading system relies on participants' ability and willingness to trade allowances. The ability to trade depends on transaction costs, while the willingness to trade depends, in particular, on a participant's evaluation of the opportunity costs of holding allowances. A better understanding of the factors related to a participant's decision whether and how to trade allowances helps explain the performance of an emissions-trading system and provides guidance for its design. In this paper, we analyse companies' allowances-trading behaviour for the first ten years of the EU ETS.

Our analyses extend previous studies for earlier periods of the EU ETS, yet we rely on a broader set of trading indicators. In addition to transaction volumes, we also consider *transaction frequency*, the *use of intermediaries*, and the *use of forwards and futures* markets. Our findings are similar for these four indicators. We find that trading behaviour is related to the size of a company, its net position (the difference between its free allocation and its verified emissions), its sector affiliation, productivity, and location. Larger companies, those with higher (absolute) *net positions*, companies operating in the *energy* and the *carbon leakage* sectors (compared with those in non-carbon leakage industries) and those with higher *productivity* are typically more likely to participate in the market and also to use the market more intensively.

Further, our findings suggest that trading-related transaction costs impact trading activity in the EU ETS. Our results are consistent with previous studies that find that transaction costs fall disproportionally on smaller companies and companies with fewer installations. Similarly, we conclude that transaction costs consist of fixed and variable components. However, we find ambiguous results whether the effects of transactions costs on companies' trading activities changed over time, depending on whether we use the number of employees or installations to capture transaction costs. Considering further differences across the three trading periods, we observe that companies were generally more active in the second and third trading periods than in the first trading period. Overall, the results pertaining to factors related to companies' trading activity are consistent across trading periods. The differences we found relate mostly to sector affiliation and net position and may be explained by changes in the price of allowances and in the evolution of the design of the EU ETS over time, in particular regarding the increasing share of auctions over time.

Last but not least, we explore differences in trading behaviour between net sellers and net buyers. Our results suggest that net buyers are more likely to participate in emissions trading and to trade at higher volumes than net sellers. This asymmetry in trading behaviour possibly reflects a violation of the Coase (1960) independence property. If market participants receive generous allowance budgets, they eventually build long positions. Our results imply that these companies trade less intensively, distorting the allowances market.

We rationalize this asymmetric behaviour by citing differences in the actual or perceived opportunity costs of holding allowances between net sellers and net buyers. We further observe that this asymmetry decreases over time, possibly owing to institutional changes in the EU ETS (length of trading periods, emergence of intermediaries and derivatives markets) and learning effects on the side of companies.

To derive these findings we employ a dataset that combines information from various databases on trading activities and company characteristics. While this yields a rich set of information, some caveats remain. For example, for several accounts in the EUTL we could not match the name of the operator with the name of a company in the ORBIS database. Likewise, for many companies, the ORBIS database did not provide information indicating company characteristics. Our analysis pertaining to forwards and futures is based on information for typical delivery dates, which may result in a coarse approximation of actual transactions of forwards and futures as we cannot account for the transactions related to derivatives before they are delivered to the final buyer. In addition, data availability limitations prevented us from including information on banked allowances. Because of the rules on banking and borrowing in the EU ETS, including this information would affect the net positions of net buyers and net sellers asymmetrically. Similarly, accounting for transactions of allowances which are internal to companies may affect some of our results.

Our empirical findings have important policy implications. It is likely that the higher share of auctioning we observed from 2013 onwards has already increased companies' ability and willingness to actively participate in emissions trading and thus has likely increased efficiency. Transaction costs for small emitters and the asymmetry involved in assessing the opportunity costs of holding allowances between net buyers and net sellers remain issues to be resolved. Transaction costs for small emitters could be reduced by addressing barriers that prevent these companies from participating in the market, in particular in auctions. One example of how this could be done is the use of an electronic bulletin board as a trading institution that would be more accessible than an exchange for smaller companies (e.g. Cason and Gangadharan 1998).

For companies continuing to receive free allocations (e.g. because of concerns about carbon leakage), consignment auctions could be implemented. These revenue-neutral auctions require that free allocation be offered at auction, with the original holder receiving the financial value of allowances determined in the auction, while allowances themselves go to the highest bidder. Consignment auctions involve low administrative costs and enhance recognition of opportunity costs (Burtraw and McCormack 2017). A more radical approach involves replacing free allocation of allowances to carbon leakage sectors by a carbon border-adjustment mechanism, as currently discussed at EU level. This would further the transition of the EU ETS towards full auctioning and likely enhance price discovery and increase efficiency in the system.

Appendix 1: Construction of the Database

Compiling of the Data

The Union registry is an electronic database managed by the European Commission that records all allowance transactions carried out under the EU ETS, including the allocation and surrendering of allowances, but also all transactions taking place between market participants. The European Union Transaction Log (EUTL) monitors, records, and authorizes all transactions occurring in the Union registry. Via the EUTL, the European Commission publishes data on allowance transactions as well as details from the Union registry. This information is now available on a three-year delay. The data can be downloaded free of charge (https://ec.europa.eu/clima/ets/).

In the EUTL transactions take place between registered accounts. All liable installations covered by the EU ETS are required to open an Operator Holding Account (OHA) for stationary installations or aircraft operator account (AOA) in the Union registry. In addition to these mandatory accounts, Person Holding Accounts (PHAs) and Trading Accounts (TAs) can be opened voluntarily in the Union registry for trading purposes.[15] Finally, a number of administrative accounts exist that belong either to the EU or to individual countries and are used for, amongst other procedures, the issuance, allocation, auctioning, or deletion of allowances.

On the account level, the EUTL includes information indicating the name of the account, the registry in which the account is registered, the related company registration number, and the associated account holder and installation. For account holders we know the name and address of the main account representative. For installations we know the type of activity and the address, and compliance data, including annual allocations, verified emissions, and surrendered allowances.

The EUTL records transfers of allowances between two accounts, providing information about the accounts involved, transaction types, transaction dates, and the number of allowances. Trading in futures and forwards is recorded only at the expiration date when a derivative is delivered to a buyer. The EUTL does not reveal information on prices per EUA or total payments.

Until 2012, a decentralized system of national registries existed. These registries were aggregated and checked in the Community Independent Transaction Log (CITL). In 2012, information was migrated from the individual registries to a single EU-wide registry and the CITL was replaced by the EUTL. In this context, all installations received new OHAs, i.e. all banked allowances had to be transferred from the old accounts to the new accounts, requiring a high number of internal transfers (see "Matching of Former and Current OHA").

In addition to EUTL data containing ETS-related information, we also use financial data on the liable companies from the ORBIS database operated by Bureau van Dijk. We use financial data on the number of employees, revenues, industry classification (NACE), the company registration number and the home country of a company. To match the EUTL and ORBIS datasets, we relied primarily on the company registration number, the account name, and addresses of account holders (see "Matching of EUTL Accounts with Companies in the ORBIS Database").

For the empirical analyses of transactions we consider only transactions involving OHAs, PHAs, or TAs. Thus, we do not consider transactions involving authorities such as the primary allocation or the surrendering of allowances. Because these EUA transactions are regulatory requirements rather than outcomes of deliberate decisions, they are not relevant in the context of this research.

[15] TAs were introduced only in 2013 and allow, in contrast to PHAs, trading in real time, while PHAs are delayed by 26 h (Art. 39.3 Registry Regulation No 389/2013). The majority of PHAs and TAs are opened by non-liable companies such as financial intermediaries as well as liable companies that use them to manage compliance and trading activities (Betz and Schmidt 2015; Cludius and Betz 2020). Some PHAs and TAs are held by non-governmental organizations or private individuals.

After we matched the company information obtained from the ORBIS to the transaction-level dataset, we set up a panel dataset at the level of individual companies for our period of analysis. Some trades were carried out by accounts that we were not able to link to an ORBIS company; these involved mainly PHAs and TAs. However, we did not exclude these trades completely from our analyses. For example, if two PHAs traded with each other but only the transferor had a link to ORBIS, that transfer would be included in the transfer volume for that company in our dataset. Because the buyer did not have a link to ORBIS, however, this transaction could not be included on the buyer side. We believe that omitting these transactions does not significantly affect the results of our analysis, because the relevant company-level transaction volumes, which are the subject of our analysis, are not affected by this adjustment. Eventually, data on allocations, verified emissions, and surrendered EUAs were aggregated at the company level.

In total, we have 40,320 accounts in the initial list, of which 6466 could not be matched with ORBIS. The others were then aggregated to 15,014 companies. For our multivariate analyses the dataset includes fewer companies because we only include EUTL activities (but not aircraft operators) where NACE codes were available. We also excluded all observations where both verified emissions and allocations were zero, thus ensuring that plants that have ceased operations but are still listed in the EUTL were excluded. This leaves us with 8767 companies. Of those, information on the number of employees, sales, and profits was available for 6964 companies. Finally, we eliminated all observations where allocation exceeded verified emissions by a factor of ten to limit the effects of errors in the EUTL on our results. This left us with 6611 companies. Because of collinearity in the data matrix the samples available for the econometric analyses are somewhat smaller and vary across analyses.

We also tried to track company banking of EUAs but found substantial inconsistencies in the data when adding up the banked allowances over time. For example, in the wake of a reorganization of the EUTL in 2012, in many cases banked allowances from the second trading period appeared to not have been adequately transferred to the third trading period.

Matching of Former and Current OHA

The reorganization of the EUTL in 2012 led to new account types such as aircraft operating holding accounts. Hence, each installation needed to be associated with a new OHA. However, the EUTL provides the current OHA related to an installation only, not the OHA that was in place before the regime switch. To infer the previous OHA we used the following procedure[16]:

1. Matching the account name to the installation name and accepting matches if they are unique.
2. Matching the account address to the installation address and accepting matches if they are unique.
3. Matching on allocation information: In this stage, we use installation-level information on the amount of allowances allocated and surrendered and search for the corresponding transaction with the same amount of allowances and an administrative account of the respective registry involved. Again, only unique matches are accepted. We start with allocations followed by surrendering transfers.

[16] A more complete description of the processing of the EUTL data is available in Abrell (2021). The compiled data set is available for download under https://euets.info/background.

This procedure allowed us to match more than 99% (i.e. 12,894 of 13,001) of the current OHAs to their OHAs before the regime switch.

Matching of EUTL Accounts with Companies in the ORBIS Database

Since 2012 operators of accounts are obliged to report a VAT registration number within the EUTL. This can be either a national or European VAT number. Because the ORBIS database also uses these VAT numbers a direct matching of accounts between the two databases based on the VAT number should be possible. However, because of reporting errors and differences in the formatting a direct matching was not feasible. We therefore use fuzzy matching based on a VAT number, the name of the account associated with that number, and the address of the account contact. These variables are used in automatic ORBIS batch searching using the account data as criteria for the search in the ORBIS database. Batch searching returns a number of possible matches together with the matching score. We then select the final match by inspecting the quality of the matches of the single fields.

Appendix 2: Descriptive Statistics

See Tables 3, 4 and 5.

Table 3 Descriptive statistics for 2005–2014 (for largest sample used in Table 2)

	Mean	Std. Dev		
		Overall	Between	Within
Total transactions (in metric tons of CO_2eq.)	514,990	7,248,713	5,720,526	4,114,349
Transaction frequency	3.37	13.2	10.716	6.604
Use of intermediaries	0.242	0.797	0.583	0.528
Use of forwards and futures (in metric tons of CO_2eq.)	62,199	1,525,535	1,398,514	629,350
Net position (in metric tons of CO_2eq.)	– 10,170	820,983	599,720	536,386
Carbon leakage	0.419	0.493	0.494	0
Energy	0.231	0.421	0.408	0
Productivity (in 1000 Euro/employee)	13.7	142	230.1	51.9
Employees	1771	14,109	10,728	2351
Number of installations	2.16	3.41	2.96	0
Region 1 (AT, DE, LI)	0.167	0.373	0.376	0
Region 2 (BE, FR, NL)	0.13	0.336	0.347	0
Region 3 (GR, IT, PT, ES, CY, MT)	0.263	0.44	0.450	0
Region 4 (EE, LT, LV, PL)	0.105	0.307	0.308	0
Region 5 (CZ, HU, SI, SK)	0.124	0.329	0.307	0
Region 6 (DK, FI, IS, NO, SE)	0.090	0.286	0.263	0
Region 7 (UK, IE)	0.080	0.271	0.259	0
Region 8 (BG, HR, RO)	0.042	0.201	0.218	0
Number of companies	6316			
Number of observations	35,056			

Table 4 Descriptive statistics by trading period (for largest sample used in Table 7)

	2005–2007		2008–2012		2013–2014	
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Total transactions (in metric tons of CO_2eq.)	230,904	2,857,846	605,041	7,940,905	628,648	8,849,416
Transaction frequency	2.18	8.9	4.02	15.7	3.24	10.9
Use of intermediaries	0.111	0.406	0.309	0.971	0.238	0.657
Use of forwards and futures (in metric tons of CO_2eq.)	17,270	299,727	77,206	1,520,003	78,425	2,209,160
Net position (in metric tons of CO_2eq.)	11,425	411,604	16,137	640,062	−94,622	1,355,406
Carbon leakage	0.422	0.494	0.402	0.49	0.453	0.498
Energy	0.241	0.428	0.25	0.433	0.177	0.381
Productivity (in 1000 Euro/employee)	12.3	180	13.4	112	16.1	153
Employees	1913	14,540	1748	13,979	1664	13,909
Number of installations	2.16	3.44	2.16	3.43	2.16	3.34
Region 1 (AT, DE, LI)	0.198	0.398	0.141	0.348	0.19	0.393
Region 2 (BE, FR, NL)	0.147	0.354	0.115	0.319	0.146	0.353
Region 3 (GR, IT, PT, ES, CY, MT)	0.2	0.4	0.277	0.447	0.301	0.459
Region 4 (EE, LT, LV, PL)	0.144	0.351	0.112	0.316	0.045	0.208
Region 5 (CZ, HU, SI, SK)	0.131	0.337	0.126	0.332	0.111	0.314
Region 6 (DK, FI, IS, NO, SE)	0.104	0.306	0.090	0.286	0.075	0.263
Region 7 (UK, IE)	0.063	0.244	0.091	0.287	0.073	0.26
Region 8 (BG, HR, RO)	0.013	0.115	0.049	0.217	0.059	0.235
Number of companies	3643		4969		4306	
Number of observations	8939		18,171		7946	

Table 5 Descriptive statistics for net-buyers and net-sellers for 2005–2014 (for largest sample used in Tables 12 and 13)

	Net buyers		Net sellers	
	Mean	Std. Dev	Mean	Std. Dev
Total transactions (in metric tons of CO_2eq.)	956,907	10,167,180	313,478	5,407,431
Transaction frequency	4.12	15.0	3.03	12.3
Use of intermediaries	0.22	0.703	0.252	0.836
Use of forwards and futures (in metric tons of CO_2eq.)	115,316	2,106,804	37,977	1,167,371
Net position (in metric tons of CO_2eq.)	− 173,054	1,380,057	64,105	308,756
Carbon leakage	0.353	0.478	0.449	0.497
Energy	0.271	0.445	0.213	0.409
Productivity (in 1000 Euro/employee)	23.3	222	9.37	81.8
Employees	1881	16,289	1721	12,994
Number of installations	2.42	4.08	2.04	3.05
Region 1 (AT, DE, LI)	0.194	0.395	0.154	0.361
Region 2 (BE, FR, NL)	0.119	0.324	0.135	0.342
Region 3 (GR, IT, PT, ES, CY, MT)	0.273	0.446	0.258	0.437
Region 4 (EE, LT, LV, PL)	0.066	0.248	0.123	0.329
Region 5 (CZ, HU, SI, SK)	0.093	0.29	0.138	0.345
Region 6 (DK, FI, IS, NO, SE)	0.122	0.327	0.076	0.265
Region 7 (UK, IE)	0.087	0.282	0.076	0.266
Region 8 (BG, HR, RO)	0.0489	0.214	0.04	0.196
Number of companies	4106		5478	
Number of observations	10,979		24,077	

Appendix 3: Estimated Average Marginal Effects for Participation Decision

See Table 6.

Table 6 Estimated average marginal effects for participation decision for 2005–2014—*Total transactions* and *use of forwards*

	Total transactions	Use of forwards and futures
Net position	0.039*** (0.002)	0.009*** (0.001)
Carbon leakage	0.013** (0.006)	0.001 (0.004)
Energy	0.063*** (0.008)	0.022*** (0.005)
Productivity	0.033*** (0.006)	0.009** (0.004)
Employees	0.016** (0.006)	0.009** (0.004)
Installations	0.024*** (0.001)	0.002*** (0.000)
Period 2	0.167*** (0.006)	0.079*** (0.004)
Period 3	0.165*** (0.007)	0.026*** (0.005)
Region 2 (BE, FR, NL)	−0.073*** (0.009)	−0.039*** (0.005)
Region 3 (GR, IT, PT, ES, CY, MT)	0.009 (0.008)	−0.047*** (0.005)
Region 4 (EE, LT, LV, PL)	−0.125*** (0.011)	−0.074*** (0.007)
Region 5 (CZ, HU, SI, SK)	−0.010 (0.010)	−0.055*** (0.006)
Region 6 (DK, FI, IS, NO, SE)	0.115*** (0.011)	−0.018*** (0.006)
Region 7 (UK, IE)	−0.018* (0.011)	−0.064*** (0.006)
Region 8 (BG, HR, RO)	−0.048*** (0.014)	−0.126*** (0.011)

*$p<0.10$; **$p<0.05$; ***$p<0.01$

Appendix 4: Results by Trading Period

See Tables 7, 8 and 9.

Table 7 Results by trading period—*Total transactions*

	Total transactions 2005–2007		Total transactions 2008–2012		Total transactions 2013–2014	
	Participation	Intensity	Participation	Intensity	Participation	Intensity
Net position	0.124*** (0.021)	0.235*** (0.072)	0.114*** (0.011)	0.415*** (0.040)	0.029 (0.025)	0.134*** (0.052)
Carbon leakage	0.150*** (0.038)	0.228** (0.112)	0.097*** (0.03)	0.499*** (0.060)	0.102*** (0.032)	0.293*** (0.085)
Energy	0.195*** (0.057)	0.461*** (0.145)	0.226*** (0.036)	0.807*** (0.089)	0.242*** (0.057)	0.437*** (0.132)
Productivity	0.391*** (0.072)	0.443*** (0.188)	0.185*** (0.037)	0.399*** (0.065)	0.039 (0.053)	0.021 (0.117)
Employees	0.340*** (0.079)	0.310** (0.184)	0.076** (0.040)	0.222*** (0.039)	0.017 (0.079)	0.372 (0.406)
Installations	0.048*** (0.014)	0.059*** (0.016)	0.070*** (0.021)	0.071*** (0.014)	0.103*** (0.015)	0.091*** (0.017)
Region 2 (BE, FR, NL)	−0.280*** (0.055)	0.236* (0.167)	−0.271*** (0.055)	−0.702*** (0.109)	−0.040 (0.052)	−0.167* (0.129)
Region 3 (GR, IT, PT, ES, CY, MT)	−0.299*** (0.043)	0.344** (0.174)	0.027 (0.045)	−0.395*** (0.064)	0.288*** (0.047)	−0.167* (0.105)
Region 4 (EE, LT, LV, PL)	−0.503*** (0.061)	0.166 (0.253)	−0.325*** (0.056)	−0.448*** (0.123)	−0.148** (0.084)	−0.535*** (0.17)
Region 5 (CZ, HU, SI, SK)	−0.148*** (0.047)	0.261** (0.128)	0.000 (0.056)	−0.310*** (0.084)	−0.005 (0.054)	−0.377*** (0.152)
Region 6 (DK, FI, IS, NO, SE)	0.360*** (0.052)	0.298** (0.178)	0.356*** (0.068)	−0.474*** (0.126)	0.015 (0.085)	−0.469*** (0.165)
Region 7 (UK, IE)	0.041 (0.065)	0.475*** (0.136)	−0.092* (0.064)	−0.625*** (0.100)	0.036 (0.073)	−0.014 (0.135)
Region 8 (BG, HR, RO)	−0.297*** (0.114)	−0.257 (0.256)	−0.216*** (0.070)	0.227* (0.159)	0.248*** (0.09)	0.029 (0.137)
Mills ratio		0.885 (0.715)		2.132*** (0.507)		0.885 (0.715)
Mean net position	0.067*** (0.022)	0.633*** (0.042)	0.112*** (0.011)	0.570*** (0.043)	0.161*** (0.027)	0.774*** (0.061)
Mean productivity	−0.367*** (0.076)	−0.293* (0.190)	−0.248*** (0.040)	−0.253*** (0.083)	−0.015 (0.056)	0.120 (0.11)
Mean employees	−0.327*** (0.080)	−0.156 (0.178)	−0.135*** (0.044)	−0.078* (0.048)	−0.014 (0.082)	−0.237 (0.411)
Constant	−2.010*** (0.099)	−0.612 (1.459)	−1.499*** (0.079)	−1.271** (0.755)	−1.816*** (0.109)	−0.657 (0.776)
Log likelihood	−12,272.94		−29,950.85		−14,098.43	
χ^2 (Prob > χ^2)	5781.52 (0.000)		20,738.16 (0.000)		6006.33 (0.000)	
Number of companies	3643		4969		4306	
Number of observations	8939		18,171		7946	

*$p<0.10$; **$p<0.05$; ***$p<0.01$

Table 8 Results by trading period—*Transaction frequency* and *use of intermediaries*

	Transaction frequency 2005–2007	Transaction frequency 2008–2012	Transaction frequency 2013–2014	Use of intermediaries 2005–2007	Use of intermediaries 2008–2012	Use of intermediaries 2013–2014
Net position	0.099* (0.052)	0.077*** (0.015)	0.042 (0.027)	0.105* (0.057)	0.117*** (0.021)	0.0823** (0.040)
Carbon leakage	0.252*** (0.068)	0.127** (0.051)	0.149*** (0.049)	0.072 (0.115)	0.215*** (0.080)	0.267*** (0.086)
Energy	0.385*** (0.089)	0.364*** (0.070)	0.425*** (0.102)	0.270** (0.138)	0.173* (0.103)	0.459*** (0.132)
Productivity	0.021 (0.111)	0.207*** (0.056)	0.087 (0.057)	0.376*** (0.108)	0.193*** (0.074)	0.175** (0.084)
Employees	0.222** (0.090)	0.143** (0.057)	−0.033 (0.118)	0.305** (0.139)	0.108* (0.062)	0.074 (0.139)
Installations	0.149*** (0.013)	0.161*** (0.013)	0.170*** (0.014)	−0.000 (0.011)	0.028*** (0.010)	0.027*** (0.010)
Region 2 (BE, FR, NL)	−0.278*** (0.092)	0.007 (0.223)	0.001 (0.121)	−0.414** (0.166)	−0.601** (0.290)	−0.681*** (0.206)
Region 3 (GR, IT, PT, ES, CY, MT)	−0.334*** (0.074)	−0.017 (0.084)	0.176** (0.068)	−0.158 (0.151)	−0.275** (0.130)	−0.253** (0.105)
Region 4 (EE, LT, LV, PL)	−0.445*** (0.112)	−0.196** (0.086)	−0.147 (0.108)	−0.299* (0.178)	−0.518*** (0.121)	0.0276 (0.152)
Region 5 (CZ, HU, SI, SK)	−0.076 (0.097)	−0.077 (0.073)	−0.162** (0.081)	0.104 (0.149)	0.293*** (0.104)	0.738*** (0.103)
Region 6 (DK, FI, IS, NO, SE)	0.456*** (0.122)	0.211* (0.113)	0.090 (0.126)	−0.343 (0.228)	−1.042*** (0.165)	−0.592*** (0.188)
Region 7 (UK, IE)	0.090 (0.132)	−0.267*** (0.073)	0.055 (0.147)	−0.253 (0.203)	−1.045*** (0.152)	−0.815*** (0.224)
Region 8 (BG, HR, RO)	−0.423** (0.186)	−0.108 (0.102)	0.138 (0.120)	−2.929*** (0.977)	−0.332** (0.151)	0.470*** (0.153)
Mean net position	0.179*** (0.053)	0.161*** (0.023)	0.262*** (0.042)	0.208*** (0.064)	0.135*** (0.032)	0.007 (0.055)
Mean productivity	0.146 (0.122)	−0.145*** (0.049)	0.196 (0.209)	−0.384*** (0.127)	−0.238*** (0.073)	−0.149 (0.096)
Mean employees	−0.114 (0.092)	−0.035 (0.058)	−0.018 (0.180)	−0.234* (0.140)	−0.0361 (0.068)	0.0602 (0.137)
Constant	−3.598*** (0.143)	−2.447*** (0.138)	−2.515*** (0.128)	−5.510*** (0.278)	−3.847*** (0.226)	−3.292*** (0.192)
Log likelihood	−13,683.75	−39,521.30	−15,384.61	−2773.90	−10,173.36	−4269.09
χ^2 (Prob > χ^2)	1796.20 (0.000)	5972.98 (0.000)	3147.49 (0.000)	2749.99 (0.000)	2404.24 (0.000)	2018.47 (0.000)
Number of companies	3643	4969	4306	3643	4969	4306
Number of observations	8939	18,171	7946	8939	18,171	7946

$^*p<0.10$; $^{**}p<0.05$; $^{***}p<0.01$

Table 9 Results by trading period—*Use of forwards and futures*

	Use of forwards and futures 2005–2007[a]		Use of forwards and futures 2008–2012		Use of forwards and futures 2013–2014	
	Participation	Intensity	Participation	Intensity	Participation	Intensity
Net position	0.093** (0.051)	0.098 (0.127)	0.054*** (0.020)	0.293*** (0.090)	0.099** (0.044)	0.872*** (0.263)
Carbon leakage	0.171** (0.074)	−0.147 (0.229)	0.159*** (0.047)	0.806*** (0.273)	0.019 (0.072)	−0.128 (0.239)
Energy	0.356*** (0.091)	0.450* (0.290)	0.286*** (0.063)	1.751*** (0.490)	0.391*** (0.098)	3.317*** (0.844)
Productivity	0.193*** (0.082)	−0.062 (0.413)	0.000 (0.038)	0.125 (0.099)	−0.015 (0.109)	−0.592** (0.343)
Employees	0.328*** (0.095)	−0.197 (0.638)	−0.058 (0.046)	−0.081 (0.152)	−0.116 (0.110)	−0.440 (0.787)
Installations	0.013** (0.007)	−0.002 (0.016)	0.015*** (0.005)	0.051*** (0.020)	0.011* (0.008)	0.063*** (0.020)
Region 2 (BE, FR, NL)	0.015 (0.099)	0.298** (0.221)	−0.375*** (0.058)	−1.915*** (0.635)	−0.246*** (0.083)	−2.313*** (0.538)
Region 3 (GR, IT, PT, ES, CY, MT)	−0.204** (0.099)	0.465* (0.312)	−0.335*** (0.051)	−2.002*** (0.566)	−0.262*** (0.090)	−3.377*** (0.614)
Region 4 (EE, LT, LV, PL)	−0.156* (0.102)	0.654*** (0.269)	−0.584*** (0.074)	−2.611*** (0.965)	−0.490*** (0.135)	−4.051*** (1.099)
Region 5 (CZ, HU, SI, SK)	−0.347*** (0.099)	0.384* (0.288)	−0.443*** (0.064)	−2.093*** (0.737)	−0.474*** (0.105)	−3.823*** (0.954)
Region 6 (DK, FI, IS, NO, SE)	0.368*** (0.090)	0.009 (0.282)	−0.253*** (0.058)	−1.793*** (0.414)	−0.105 (0.092)	−0.959*** (0.290)
Region 7 (UK, IE)	−0.131 (0.104)	0.751* (0.472)	−0.458*** (0.070)	−2.390*** (0.833)	−0.267*** (0.094)	−2.111*** (0.666)
Region 8 (BG, HR, RO)	−32.608*** (12.506)	−23.937*** (6.976)	−1.101*** (0.128)	−4.336*** (1.814)	−0.456*** (0.141)	−3.450*** (0.924)
Mills ratio				5.522*** (1.986)		9.341*** (2.534)
Mean net position	0.102** (0.057)	0.367*** (0.124)	0.130*** (0.022)	0.977*** (0.223)	0.085** (0.041)	0.903*** (0.215)
Mean productivity	−0.132* (0.082)	0.288 (0.444)	0.015 (0.040)	0.292*** (0.113)	−0.011 (0.114)	0.868*** (0.358)
Mean employees	−0.266*** (0.096)	0.465 (0.647)	0.105** (0.046)	0.607*** (0.208)	0.170* (0.115)	1.151* (0.808)
Constant	−4.038*** (0.179)	3.060*** (0.472)	−3.000*** (0.117)	−13.791** (6.162)	−3.395*** (0.194)	−28.266*** (8.914)
Log likelihood	−2402.13		−10,138.10		−2990.86	
χ^2 (Prob > χ^2)	1075.06 (0.000)		2485.04 (0.000)		505.02 (0.000)	
Number of companies	3643		4969		4306	
Number of observations	8939		18,171		7946	

[a]Model converged assuming zero correlation between equations only

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$

Appendix 5: Results for *Total Transactions* with Asymmetric Response for Net Sellers and Net Buyers

See Tables 10 and 11.

Table 10 Results for 2005–2014—*Total transactions* with interaction between net position and net sellers

	Total transactions	
	Participation	Intensity
Net position X net sellers	−0.036*** (0.002)	−0.027*** (0.005)
Net position	0.160*** (0.009)	0.441*** (0.026)
Carbon leakage	0.092*** (0.021)	0.273*** (0.045)
Energy	0.173*** (0.033)	0.411*** (0.063)
Productivity	0.040** (0.024)	0.130*** (0.032)
Employees	0.017 (0.021)	0.105*** (0.030)
Installations	0.062*** (0.015)	0.058*** (0.009)
Period 2	0.493*** (0.018)	1.062*** (0.079)
Period 3	0.371*** (0.024)	0.658*** (0.069)
Region 2 (BE, FR, NL)	−0.199*** (0.037)	−0.279*** (0.072)
Region 3 (GR, IT, PT, ES, CY, MT)	0.014*** (0.031)	−0.193*** (0.048)
Region 4 (EE, LT, LV, PL)	−0.341*** (0.039)	−0.335*** (0.088)
Region 5 (CZ, HU, SI, SK)	−0.032 (0.036)	−0.197*** (0.071)
Region 6 (DK, FI, IS, NO, SE)	0.291*** (0.047)	−0.274*** (0.080)
Region 7 (UK, IE)	−0.057 (0.046)	−0.277*** (0.077)
Region 8 (BG, HR, RO)	−0.135*** (0.055)	0.106 (0.099)
Mills ratio		1.653*** (0.261)
Mean net position	0.103*** (0.011)	0.631*** (0.026)
Mean productivity	−0.082*** (0.026)	−0.043 (0.039)
Mean employees	−0.050** (0.021)	0.005 (0.033)
Constant	−2.201*** (0.074)	−2.335*** (0.261)
Log likelihood	−56,154.31	
χ^2 (Prob > χ^2)	33,774.66 (0.000)	
Number of companies	6316	
Number of observations	35,056	

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$

Table 11 Results by trading period—*Total transactions* with interaction between net position and net sellers

	Total transactions 2005–2007		Total transactions 2008–2012		Total transactions 2013–2014	
	Participation	Intensity	Participation	Intensity	Participation	Intensity
Net position X net sellers	−0.066*** (0.005)	−0.070*** (0.012)	−0.035*** (0.004)	−0.033* (0.021)	−0.024*** (0.003)	−0.006 (0.019)
Net position	0.183*** (0.024)	0.285*** (0.057)	0.150*** (0.012)	0.433*** (0.128)	0.051** (0.026)	0.143* (0.089)
Carbon leakage	0.133*** (0.040)	0.223*** (0.089)	0.102*** (0.031)	0.498*** (0.103)	0.133*** (0.034)	0.302** (0.16)
Energy	0.201*** (0.058)	0.427*** (0.123)	0.202*** (0.043)	0.742*** (0.150)	0.223*** (0.063)	0.443** (0.224)
Productivity	0.359*** (0.069)	0.368*** (0.144)	0.169*** (0.037)	0.360*** (0.134)	0.033 (0.052)	0.027 (0.134)
Employees	0.321*** (0.078)	0.254** (0.141)	0.065* (0.040)	0.201*** (0.058)	0.025 (0.077)	0.374 (0.595)
Installations	0.044*** (0.014)	0.052*** (0.011)	0.066*** (0.026)	0.066*** (0.024)	0.105*** (0.016)	0.092*** (0.031)
Region 2 (BE, FR, NL)	−0.230*** (0.054)	0.308*** (0.119)	−0.265*** (0.059)	−0.660* (0.471)	−0.027 (0.058)	−0.164 (0.347)
Region 3 (GR, IT, PT, ES, CY, MT)	−0.321*** (0.043)	0.288*** (0.128)	0.014*** (0.056)	−0.410 (0.230)	0.305*** (0.059)	−0.149*** (0.12)
Region 4 (EE, LT, LV, PL)	−0.487*** (0.058)	0.214* (0.166)	−0.333*** (0.065)	−0.416 (0.529)	−0.127* (0.088)	−0.530* (0.379)
Region 5 (CZ, HU, SI, SK)	−0.139*** (0.050)	0.293*** (0.113)	0.004 (0.055)	−0.299 (0.246)	0.015 (0.064)	−0.372 (0.332)
Region 6 (DK, FI, IS, NO, SE)	0.362*** (0.051)	0.277*** (0.113)	0.315*** (0.077)	−0.556*** (0.127)	0.079 (0.093)	−0.446*** (0.183)
Region 7 (UK, IE)	−0.021 (0.066)	0.386*** (0.125)	−0.095* (0.066)	−0.618** (0.295)	0.039 (0.082)	−0.014 (0.223)
Region 8 (BG, HR, RO)	−0.353*** (0.113)	−0.367** (0.211)	−0.243*** (0.069)	0.232 (0.498)	0.264*** (0.095)	0.045 (0.148)
Mills ratio		0.861** (.383)		1.938 (1.7)		1.779 (2.208)
Mean net position	0.093*** (0.023)	0.662*** (0.039)	0.119*** (0.014)	0.562 (0.098)	0.146*** (0.028)	0.773*** (0.15)
Mean productivity	−0.365*** (0.074)	−0.254* (0.155)	−0.251*** (0.041)	−0.226 (0.207)	−0.018 (0.055)	0.115 (0.14)
Mean employees	−0.313*** (0.079)	−0.112 (0.140)	−0.126*** (0.043)	−0.053 (0.099)	−0.025 (.079)	−0.238 (0.605)
Constant	−2.228*** (0.107)	−0.705 (0.795)	−1.585*** (0.117)	−0.985 (2.324)	−1.787*** (0.128)	−0.781 (3.364)
Log likelihood	−12,123.59		−29,877.91		−14,071.89	
χ^2 (Prob > χ^2)	5934.80 (0.000)		20,781.87 (0.000)		6028.76 (0.000)	
Number of companies	3643		4969		4306	
Number of observations	8939		18,171		7946	

*$p<0.10$; **$p<0.05$; ***$p<0.01$

Appendix 6: Results for Net Buyers and Net Sellers

See Tables 12 and 13.

Table 12 Results for net buyers 2005–2014

	Total transactions		Transaction frequency	Use of intermediaries	Use of forwards and futures	
	Participation	Intensity			Participation	Intensity
Net position	0.138*** (0.012)	0.404*** (0.040)	0.044** (0.018)	0.044*** (0.015)	0.075*** (0.024)	0.588*** (0.112)
Carbon leakage	0.010 (0.034)	0.161*** (0.064)	0.090* (0.048)	0.154* (0.092)	0.050 (0.064)	0.173 (0.183)
Energy	0.289*** (0.057)	0.579*** (0.135)	0.461*** (0.081)	0.365*** (0.129)	0.315 *** (0.080)	2.401*** (0.524)
Productivity	0.072* (0.045)	0.167*** (0.062)	0.202*** (0.074)	0.116 (0.135)	0.027 (0.062)	0.080 (0.235)
Employees	0.107*** (0.037)	0.260*** (0.078)	0.295*** (0.089)	0.285** (0.131)	0.063 (0.053)	0.511** (0.225)
Installations	0.056*** (0.019)	0.051*** (0.011)	0.144*** (0.012)	0.017* (0.010)	0.012** (0.007)	0.040*** (0.014)
Period 2	0.216*** (0.036)	0.722*** (0.086)	0.387*** (0.093)	0.551*** (0.103)	0.017 (0.072)	2.491*** (0.387)
Period 3	0.143*** (0.036)	0.429*** (0.084)	0.333*** (0.012)	0.592*** (0.105)	0.021 (0.055)	1.254*** (0.215)
Region 2 (BE, FR, NL)	−0.206*** (0.056)	−0.398*** (0.121)	−0.063 (0.122)	−0.614*** (0.196)	−0.337*** (0.093)	−2.353*** (0.600)
Region 3 (GR, IT, PT, ES, CY, MT)	0.091** (0.053)	−0.147** (0.076)	0.023 (0.060)	−0.555*** (0.116)	−0.474*** (0.071)	−3.553*** (0.674)
Region 4 (EE, LT, LV, PL)	−0.351*** (0.069)	−0.424*** (0.146)	−0.138 (0.099)	−0.227 (0.158)	−0.419*** (0.118)	−2.804*** (0.620)
Region 5 (CZ, HU, SI, SK)	−0.046 (0.062)	−0.407*** (0.094)	−0.072 (0.078)	0.734*** (0.111)	−0.436*** (0.110)	−2.950*** (0.608)
Region 6 (DK, FI, IS, NO, SE)	0.482*** (0.070)	−0.127 (0.160)	0.406*** (0.106)	−0.830*** (0.205)	−0.027 (0.098)	−0.576*** (0.206)
Region 7 (UK, IE)	−0.044 (0.076)	−0.226** (0.100)	−0.088 (0.109)	−0.769*** (0.172)	−0.316*** (0.110)	−1.959*** (0.492)
Region 8 (BG, HR, RO)	0.037 (0.084)	0.157* (0.119)	−0.049 (0.104)	0.215 (0.159)	−0.670*** (0.147)	−4.295*** (1.077)
Mills ratio		2.145*** (0.556)				7.607*** (1.687)
Mean net position	0.015 (0.013)	0.621*** (0.028)	0.150*** (0.027)	0.111*** (0.033)	0.317*** (0.059)	0.900*** (0.128)
Mean productivity	−0.055 (0.048)	0.010 (0.060)	−0.011 (0.078)	0.025 (0.139)	0.124** (0.056)	0.506** (0.260)
Mean employees	−0.096*** (0.038)	−0.050 (0.072)	−0.127 (0.090)	−0.140 (0.133)	0.088*** (0.028)	0.340* (0.226)

Table 12 (continued)

	Total transactions		Transaction frequency	Use of intermediaries	Use of forwards and futures	
	Participation	Intensity			Participation	Intensity
Constant	−1.377*** (0.093)	2.145*** (0.556)	−3.081*** (0.152)	−4.522*** (0.241)	−3.443*** (0.163)	7.607*** (1.687)
Log likelihood	−18,831.83		−22,858.17	−5097.55	−4945.40	
χ^2 (Prob > χ^2)	16,136.07 (0.000)		3398.16 (0.000)	2277.31 (0.000)	1499.46 (0.000)	
Number of companies	4106		4106	4106	4106	
Number of observations	10,979		10,979	10,979	10,979	

*$p < 0.10$; **$p < 0.05$; ***$p < 0.01$

Table 13 Results for net sellers 2005–2014

	Total transactions		Transaction frequency	Use of intermediaries	Use of forwards and futures	
	Participation	Intensity			Participation	Intensity
Net position	0.151*** (0.012)	0.499*** (0.029)	0.141*** (0.015)	0.146*** (0.019)	0.071*** (0.160)	0.387*** (0.110)
Carbon leakage	0.118*** (0.023)	0.318*** (0.044)	0.160*** (0.046)	0.192*** (0.070)	0.108** (0.050)	0.412** (0.183)
Energy	0.129*** (0.042)	0.408*** (0.050)	0.319*** (0.076)	0.242** (0.107)	0.254*** (0.064)	1.221*** (0.415)
Productivity	0.030 (0.028)	0.146*** (0.043)	0.037 (0.065)	0.094** (0.042)	0.032 (0.033)	0.434*** (0.135)
Employees	−0.030 (0.035)	0.051* (0.031)	0.062 (0.040)	0.006 (0.049)	0.000 (0.033)	0.196* (0.120)
Installations	0.062*** (0.013)	0.066*** (0.010)	0.173*** (0.015)	0.018* (0.010)	0.011** (0.005)	0.034** (0.020)
Period 2	0.570*** (0.024)	1.251*** (0.097)	0.641*** (0.046)	1.160*** (0.054)	−0.044 (0.036)	2.720*** (0.906)
Period 3	0.492*** (0.033)	0.825*** (0.099)	0.418*** (0.064)	0.904*** (0.073)	0.021 (0.032)	0.007 (0.262)
Region 2 (BE, FR, NL)	−0.229*** (0.044)	−0.293*** (0.081)	0.091 (0.209)	−0.463* (0.278)	−0.223*** (0.058)	−1.001*** (0.324)
Region 3 (GR, IT, PT, ES, CY, MT)	−0.055* (0.038)	−0.236*** (0.046)	0.037 (0.086)	−0.094 (0.124)	−0.187*** (0.055)	−1.220*** (0.283)
Region 4 (EE, LT, LV, PL)	−0.362*** (0.054)	−0.367*** (0.093)	−0.182** (0.088)	−0.375*** (0.125)	−0.508*** (0.066)	−1.796** (0.795)
Region 5 (CZ, HU, SI, SK)	−0.048 (0.043)	−0.137*** (0.062)	−0.029 (0.079)	0.321*** (0.108)	−0.408*** (0.066)	−1.626*** (0.659)
Region 6 (DK, FI, IS, NO, SE)	0.134*** (0.055)	−0.266*** (0.100)	0.098 (0.117)	−0.761*** (0.155)	−0.096 (0.076)	−0.788*** (0.221)
Region 7 (UK, IE)	−0.093* (0.059)	−0.347*** (0.094)	−0.142* (0.086)	−0.936*** (0.147)	−0.388*** (0.079)	−1.706*** (0.612)
Region 8 (BG, HR, RO)	−0.257*** (0.062)	0.042 (0.105)	−0.032 (0.114)	−0.227 (0.165)	−0.927*** (0.107)	−3.029** (1.467)
Mills ratio		1.842*** (0.265)				4.651*** (1.894)
Mean net position	0.146*** (0.013)	0.634*** (0.029)	0.136*** (0.032)	0.122*** (0.044)	0.588*** (0.038)	1.023*** (0.273)
Mean productivity	−0.101*** (0.028)	−0.087** (0.048)	0.043 (0.066)	−0.147*** (0.056)	0.052 (0.058)	−0.157 (0.143)
Mean employees	−0.023 (0.035)	0.004 (0.033)	0.042 (0.057)	0.065 (0.061)	0.169*** (0.018)	0.108 (0.113)
Constant	−2.713*** (0.072)	1.842*** (0.265)	−3.548*** (0.123)	−5.188*** (0.190)	−3.978 (0.117)	4.651*** (1.894)
Log likelihood	−37,001.03		−48,859.11	−12,204.41	−10,588.59	
χ^2 (Prob > χ^2)	17,620.24 (0.000)		4850.62 (0.000)	4433.21 (0.000)	1836.55 (0.000)	
Number of companies	5478		5478	5478	5478	
Number of observations	24,077		24,077	24,077	24,077	

*$p<0.10$; **$p<0.05$; ***$p<0.01$

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