Carbon Permit Holdings *

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Abstract

Based on administrative data, I construct a novel dataset of firm-level holdings of emission permits in the EU Emission Trading System. Emission permits take a sizable share on firms' balance sheets and a majority of firms hold large quantities of emission permits in excess of their emission levels. I find evidence that holders of excess permits retain permit holdings to hedge future shocks to carbon prices. Firms with excess holdings (1) trade less, (2) sell more permits when carbon price uncertainty is low, and (3) show smaller reductions in future emissions. These results are consistent with models of firms' permit trading and decarbonization behavior under risk aversion and uncertainty and provide empirical evidence that carbon price uncertainty leads to limited trading participation and excess cost of decarbonization.

Keywords: Climate, Carbon Pricing, Emission Trading, Hedging, Uncertainty

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Pricing carbon emissions is a key policy to incentivize corporate decarbonization efforts. The preferred tool to implement such pricing mechanisms for the emission of carbon are so called cap-and-trade systems. Currently, such systems cover about 18% of global carbon emissions and 75% of total emissions subject to carbon prices (World Bank, 2023). Cap-and-trade systems work via a market-based mechanism of tradable permits that allow firms to emit carbon. The regulator initially issues and allocates a limited quantity of such emission permits. Firms can then trade these emission permits among each other creating a market price of carbon emissions. One of the central benefits of cap-and-trade systems is that aggregate decarbonization objectives are achieved cost-effectively without requiring the regulator to know firms' individual marginal abatement cost (Goulder, 2013). Firms whose marginal abatement cost are below the carbon price can realize trading profits by selling emission permits to firms with higher cost to decarbonize their operations. The market mechanism is thus a key feature of cap-and-trade systems that ensures that the equilibrium holdings of emission permits reflect firms' expected decarbonization outcomes.

This paper is the first to study firms' holdings of emission permits. This is important as it allows to establish new facts on firms' equilibrium levels of permit holdings, permit trading dynamics and how permit holdings interact with firms' emission levels and permit prices. In a well-functioning emission permit market, the equilibrium allocation of permits is independent of the initial permit allocation (Montgomery, 1972; Hahn and Stavins, 2011). In turn, firms' ex post holdings of emission permits should reflect their decarbonization decisions only via their marginal abatement cost and carbon price expectations. Baldursson and von der Fehr (2004) and Yoon et al. (2024), however, show theoretically that uncertainty about future carbon prices can lead to limited trading participation and lower decarbonization outcomes for firms with ex ante large quantities of permit holdings. Based on novel data on firm-level holdings of emission permits, I provide supporting empirical evidence for these predictions.

I study firm-level emission permit holdings in the European emissions trading system (EU ETS). The EU ETS is the worldwide oldest and largest cap-and-trade system covering about 40% of the European Union's total carbon emissions. My first contribution is to provide a panel of monthly firm-level holdings of emission permits based on administrative transaction data that the EU Commission makes publicly available. Building on work by Abrell (2024), I advance and overcome empirical key challenges that allow to construct a nearly complete dataset of firms' emission permit holdings.[1] These challenges include the recovery of missing counterparty information between transactions, a consistent linking of permit holdings across time, and the identification of unique firm-level holders of emission permits. The final dataset comprises monthly holdings of emission permits of about 8,000 regulated firms (henceforth operators) and 4000 financial traders across 12 years from May 2008 until April 2020.

In the first part of this paper, I explore firm's emission permit holdings and document new related facts on the market structure and firm-level determinants of emission permit holdings. Emission permits are concentrated among few participants in the EU ETS. The largest ten operators together hold on average about 11% of total outstanding emission permits while the top ten financial traders hold a combined share of 17%. Before 2013, operators hold the vast vajority

[1]The data include permit holdings that stem from 99.9% of all transactions occurring during this period.

of emission permits while thereafter both operators and financial traders hold about 50% each. Interestingly, regulated firms source emission permits mainly from financial traders and other operators. The supply via permit auctions or secondary market exchanges play only a minor role even for large sophisticated operators. Instead, financial traders acting as intermediaries appear to be the main players on auction markets and secondary market exchanges where large volumes of permit spot and futures contracts are traded.

I then focus on the holdings of emission permits and the trading behavior of operators who are obliged to surrender a quantity of emission permits in April each year that corresponds to the level of carbon emissions of the preceding year. The value of firms' emission permit holdings on operators' balance sheets is substantial and of similar magnitude as their cash holdings. In particular after 2018, when carbon prices trippled from about 7 EUR per emission permit to more than 22 EUR/tCO2e, large holders of carbon permits decreased their cash holdings in favor of emission permits amounting to 1.4% of total assets.

At the end of each compliance year, after firms surrendered their permit obligations, operators may sell any excess permits or retain them for future use. Regulated firms may hold excess permits to hedge against future shocks to carbon prices or because of financial or market frictions. I document that many operators hold large quantities of excess permit holdings. In an average year, the median operator holds excess permits of 125% relative to current emissions. That is, after surrendering emission permits for the current year, the median firm holds permits that are sufficient to cover emissions of 1.25 times its current emission levels in the subsequent year without relying on additional permit allocations or market purchases.

I then explore the determinants of firms' excess permit holdings. Free permit allocations—emission permits that the European Commission allocates to regulated firms for free—are the single most important determinant of excess holdings explaining more than 22% of its variation within industry and compliance year. Measures of financial constraints, emission volatility, as well as current and past emission changes play only minor roles and together explain less than 3% of the total variation in firms' excess holdings. While I find financially constrained firms hold larger quantities of excess permits, the effect is small in magnitude. I also find no evidence consistent with the smoothing of accounting losses or liquidity provision as in N'Gatta et al. (2023). The fact that free permit allocations explain large parts of firms' excess holdings indicates that market frictions may prevent firms from selling their excess permits.

Turning to firms' trading participation in the emission permit market, I find overall trading activity low. In particular, firms' with above-median levels of excess permits (net permit sellers) hardly trade. The difference in trading turnover (firms' annual trading volume divided by median permit holdings) between net sellers and net buyers of emission permits is substantial. For example, the median trading turnover of the largest holders of emission permits is 73% if the firm is a net buyer and only 17% if it is a net permit seller. This difference in trading turnover between net sellers and net buyer becomes even more pronounced for firms with smaller quantities of permit holdings.

The low trading participation of net sellers may be due to uncertainty about future carbon prices. In times of high carbon price uncertainty, risk-averse firms may increase their permit hold-

ings as a precautionary hedging motive against future shocks to permit supply or decarbonization costs. To reduce exposure to uncertainty about future carbon prices, firms with ex ante large holdings of excess permits may limit the propensity to sell. In a behavioral model Yoon et al. (2024) show that carbon price uncertainty and risk aversion creates a wedge between net sellers' permit supply and net buyers' demand leading to reduced trading participation.

I test these predictions empirically based on the Carbon VIX, a market-based measure of carbon price uncertainty developed in Fuchs et al. (2024). On aggregate, I find that net sellers sell about 7% of the same year's emission obligations in months of low carbon price uncertainty while they only sell 1% during months of high carbon price uncertainty. I find similar effects at the firm-level, controlling for the demand of net permit buyers who face tight constraints to purchase emission permits at the end of each compliance cycle, for transaction costs as well as for various market and firm characteristics. A one standard deviation (or 7.69 ppt) decline in expected carbon price volatility is associated with an annual decrease of net sellers' permit holdings by 3%. This effect is economically large as in an average year net sellers sell on only 2.6% of their holdings. This effect is robust to alternative definitions of net sellers and different sub-samples. For example, I exclude observations of firms' *increases* in permit holdings providing evidence that it is net sellers' *sales* of emission permits that decrease with carbon price uncertainty.

Finally, I explore the relation between firms' excess permit holdings and decarbonization outcomes. Baldursson and von der Fehr (2004) develop a model showing that firms hedge carbon price uncertainty depending on their market position. Firms with ex ante low—or zero—excess holdings reduce exposure to carbon price uncertainty by decarbonizing their operations. In contrast, firms with ex ante large quantities of excess allowances retain those permits instead of selling them. I find strong empirical support for such an effect. Firms with low levels of excess permit holdings show large reductions in *future* emissions, in particular those that rely on additional market purchases to cover future emission obligations. Conversely, firms with large quantities of excess permit holdings hardly reduce future emissions. A 10% increase in firms' excess holdings in a given year leads to a 0.4-0.5 percentage points lower decrease in one-year-ahead carbon emissions. As the average decrease in firm-level carbon emission is about 1.2%, the economic magnitude is substantial. This relation holds within industries, controlling for marginal abatement cost, and after controlling for the level of emissions, emission volatility, current and past changes in volatility as well as the share of free permit allocations.

Contribution. This paper contributes to a growing body of literature that studies the effects of climate policies on firm behavior. There is widespread consensus that the introduction of climate mitigation policies led to reductions in firms' carbon emission both for carbon taxes (Martinsson et al., 2024; Abrell et al., 2022b) and market based cap-and-trade systems (Bayer and Aklin, 2020; Känzig, 2023; Colmer et al., 2024). There is also evidence that firms subject to climate policy move production to locations with less stringent policies (Känzig et al., 2024; Ben-David et al., 2021).

This paper focuses on firm behavior and market dynamics in cap-and-trade systems. Zaklan (2013) and Abrell et al. (2022a) study firms' trading behavior in the EU ETS based on contemporaneous permit transactions and firm-level characteristics. The new dataset on emission permit

holdings constructed in this paper allows to expand this literature by studying the level of emission permit holdings and therefore its equilibrium allocation. Hahn and Stavins (2011) discuss market conditions, such as uncertainty about future carbon prices, for which ex post permit allocation is not independent of the initial permit allocations potentiality leading to departure from the global minimum of decarbonization costs.[2] Yoon et al. (2024) directly model firms' trading behavior in cap-and-trade systems under uncertainty. If firms are loss averse, carbon price uncertainty can lead to limited permit trading and increasing cost of decarbonization. This paper provides empirical evidence supporting such mechanisms.

This study also provides insights related to firms' hedging demand and output under uncertainty. Gao et al. (2022) studies the oil market and finds an increase in oil price uncertainty leads to higher aggregate oil inventories, lower investment and output. Fuchs et al. (2024) provide a measure of carbon price uncertainty and show it negatively impacts firms' decarbonization investment. Most relevant for this study is the model of Baldursson and von der Fehr (2004) that incorporates uncertainty in a cap-and-trade setting and shows that firms' with large quantities of excess permit holdings over-rely on the usage of emission permits and under-invest in decarbonization. The findings in the paper provide complementary empirical evidence.

I. Carbon Permit Holdings

In this section, I construct and document a granular and high-frequency sample of carbon permit holdings. I first provide an overview on the fundamental mechanism and important features of the EU Emission Trading System (EU ETS). I then detail the construction of carbon permit holdings from administrative data and document new facts on firms' holdings and trading behavior of emission permits.

I.A. Emission Trading Systems

The fundamental idea of emission trading (or cap-and-trade) systems is based on seminal work of Coase (1960) who proposed to describe the problem of pollution as poorly defined property rights. If externalities such as the emission of carbon could be traded as a form of rights to property, the allocation of such property rights among private actors would be cost-optimal and independent of its initial allocation. In such emission trading systems, the regulating authority issues a limited quantity of emission permits where each permit allows regulated firms—often determined by certain sectors or corporate activities—to emit an equivalent unit of carbon. By controlling the total quantity of permits issued, the regulator implicitly sets a cap on the total volume of carbon emitted. After an initial allocation of emission permits—often via auctions or free allocation—firms can trade them in a market-based system. The resulting market price for emission permits creates incentives for firms to decarbonize their operations. Thus, the benefit of

[2]Other important conditions that may violate the independence property are transaction costs, market power, conditional allowance allocation, and regulatory differences in firms' treatment that are likely less predominant in the EU ETS (Hahn and Stavins, 2011).

such emission trading systems is that it allows for a cost efficient reduction of carbon emissions without requiring the regulator to know the firms' individual marginal abatement cost curves.

I.B. The European Emissions Trading System

Currently, 27 jurisdictions have introduced emission trading systems covering about 18% of global carbon emissions (World Bank, 2023). The EU Emission Trading System (EU ETS) is the globally largest and oldest carbon trading scheme. Initiated in 2005, the EU ETS covers about 40% of the EU's total carbon emissions.[3] It regulates emissions of more than 10,000 installations of firms operating in energy intensive manufacturing or power generation sectors as well as firms in the aviation industry operating flights within the EU. Since January 2024, the shipping sector has been added to EU ETS regulation. From 2027, firms operating in the buildings and transport sectors will be added in a separate EU-wide ETS. Also non-regulated firms such as financial intermediaries or commodity traders are allowed to participate in the trading of emission permits.

The EU Commission determines the cap on greenhouse gas emissions by issuing allowances (EUAs) that permit the emission of one ton of carbon equivalents. Until 2012, the cap was based on firms' historical emissions determined in the period 2005–2007. In 2013, the cap has been set at 2.1bn EUAs, the annual average quantity of previously issued permits. To reduce aggregate carbon emissions, this cap is reduced annually by a constant and pre-specified number of emission permits. For the period 2013–2020, this linear reduction factor was initially set at 1.74%. In subsequent steps, this factor was tightened to an annual reduction of 4.4% by 2030 consistent with a total cap reduction of 62% compared to emission levels in 2005 (European Commission, 2023).

Annual Compliance Cycle. The annual compliance cycle is a yearly procedure including the monitoring, reporting, and verification of firms' emissions followed by surrendering a corresponding quantity of emission permits to the regulating authority. Each regulated firm reports carbon emissions for a given year. Reported emissions must be verified by an accredited third-party verifier by March 31st of the following year. By the end of the compliance cycle in April 30th, the firm must surrender a number of emission permits equal to the amount of its verified emissions. This process is enforced with heavy fines and compliance rates are high. In 2022, firms representing 99% of emissions met their emission permit obligation on time (EU Commission, 2023).

Permit Allocation. Carbon emission permits are either allocated for free or auctioned off at a central auction platform. Coase (1960) and Montgomery (1972) have shown that, absent market frictions, the cost efficiency of emission reduction and final allocation of permits is independent of their initial allocation. As this "independence" property allows to ease distributional consequences of decarbonization costs, it is a primary reason for the popularity and political acceptance of emission trading systems (Hahn and Stavins, 2011). The EU Commission has made abundant use of free permit allocations to regulated firms. Until 2022, about 47.7 billion emission permits have been allocated for free while, starting from 2012, only 6.9 billion permits have been auctioned generating a revenue of EUR 167.7 billion. Firms typically receive free allocations in February each

[3]The EU ETS covers EU member countries plus Icelend, Liechtenstein and Norway and is linked with the ETS of Switzerland since January 2020.

year. Until 2012, freely allocated permits were proportional to firms' historical emissions. From 2013, firms operating in electricity generation activities ceased to receive free permit allocations. For remaining sectors permits are allocated for free primarily based on historical output and emission intensity per output benchmarks at the product-level.[4] From 2013, auctioning becomes in principle the default allocation method and the share of free allocations firms receive reduces from 80% of benchmarked emissions to 30% in 2020. However, firms operating in sectors identified at risk of carbon leakage, i.e. the risk of firms moving the production of regulated goods outside of the EU, continue to receive permits equivalent to 100% of benchmarked emissions for free.[5] The large quantities of free permit allocations frequently exceeded actual emissions of industrial firms leading to large windfall gains, in particular for firms producing cement, bricks, or lime products (de Bruyn et al., 2021).

A brief history of the EU ETS. The development of the EU ETS is often split in regulatory phases. Phase I was a pilot phase from 2005 to 2008 and permits issued during this period could could not be transferred to subsequent period. My sample starts in 2009, with the beginning of Phase II where emission permits were first "bankable", i.e. permits issued in one phase were allowed to be transferred to subsequent regulatory phases. Phase II was characterized by large permit excess supply and low prices as the quantity of permits issued was based on historical emissions and the economic downturn post 2008 led to lower demand for emission permits. Phase III (2013–2020) started with substantial regulatory changes including tighter EU-wide emission caps and more targeted allocation of free permits. To tackle the low carbon price levels, the commission decreased permit supply by postponing the auctioning of a significant number of permits. However, until the end of 2017 permit prices remained low ranging between 3.1 and 8.2 EUR. To further limit the supply of emission permits, the EU commission launched a market stability reserve in January 2019. The reserve is designed to withdraw (release) a fraction of permits in circulation each year in case the number of permits in circulation is above (below) a predetermined threshold. Within the first years of its launch, the market stability reserve absorbed an annual rate of 24% of permits in circulation. Carbon prices increased substantially from 9.2 to 25.0 EUR during 2018 in anticipation of the introduction of the market stability reserve. At the same time, the frequent policy changes in the EU ETS lead to high uncertainties about future carbon prices (Fuchs et al., 2024).

I.C. Constructing Carbon Permit Holdings

I use administrative data from the EU Commission to retrieve holdings of carbon emission permits in the EU ETS. All participants in the EU ETS must register accounts that are used to hold and trade carbon permits. With a delay of three years, the EU commission discloses individual transactions of carbon permits between accounts in a public registry.[6] These transactions include

[4] Benchmarks are based on the average emission intensity per output of the 10% most efficient installations in each sector. See Verde et al. (2018) for details on free allocation rules.

[5] The list of sectors identified at risk of carbon leakage for years 2015-2020 represent 98% of industrial carbon emissions. In an updated version of that list for years 2021-2030 94% of industrial carbon emissions are included (EU Commission, 2019).

[6] The EU Transaction Log can be accessed via `https://ec.europa.eu/clima/ets/`. I greatly benefit from work by Abrell (2024) who scrapes the information from the EU Commission's website and stores it in a relational database accessible via

a time-stamp, the number of permits transacted, and the purpose of the transaction along with account information for both transferring and receiving counterparty. Tracking transactions of individual accounts over time allows me to create a time series of granular carbon permit holdings at high frequency.

The dataset includes more than 1.8 million transactions of carbon permits between about 43,000 accounts.[7] Appendix Section A.1 contains a detailed description of data sources and sample construction. From the start of Phase II in 2008—when carbon permits were first allowed to be rolled over to subsequent years—through April 2020, I accumulate the signed quantity of received and transferred carbon permits at the account owner-month level. Hence, the amount of carbon permit holdings H of account owner i in month t is the cumulative sum of all preceding net transactions F.

$$H_{i,t} = \sum_{h=1}^{t} \Delta F_{i,h} \tag{1}$$

Retrieving accurate holdings from transactions of carbon permits involves three empirical key challenges. First, transactions must be complete. Missing or erroneous transactions at any point in time introduces a bias to the level of holdings that affect all subsequent periods making accurate empirical inference difficult. Second, holdings must be traceable over time, i.e. the identification of account ownership associated with permit holdings must be consistent over time. Connecting accounts across time is particularly relevant during the transition from EU ETS Phases II to III as, due to changes in the public registry, account holders had to close and re-open new accounts. Lastly, the ownership of accounts must be uniquely identified to account for re-allocation of carbon permits between multiple accounts owned by the same firm. While firms are not directly represented in the dataset, firm-level information can be inferred via the ownership of accounts. Hence, I use account owner and firm synonymously. I build on previous work of Abrell (2024) and make significant advances on all three dimensions that allow me to consistently observe the stock of outstanding carbon permits across firms and time. Appendix Sections A.1.A contain details on how I (1) recover missing counterparty information, (2) link carbon permit holdings across time and (3) identify and aggregate firms as unique account owners.

Account owners may own multiple accounts. Each account is assigned a unique identifier and contains information on account name, name and address of the account owner, and the account type. Importantly, information on account types allow me to distinguish operator accounts, trader accounts, and administrator accounts and therefore to infer the nature of account owners. Operator accounts can be linked to firms' installations with compliance obligations and are used to receive free permits and surrender permits in accordance with corresponding carbon emission obligations. Regulatory authorities use administrator accounts to allocate, exchange and receive surrendered permits. Non-regulated actors such as banks and commodity traders can participate in the market by opening dedicated trader accounts. In particular, large energy producers who are often also

`https://www.euets.info/`.

[7] I consider all permits allowed to be used from Phase II such as general emission allowances (EUAs), aviation allowances (AEUAs), or certified emission reduction units (CERs).

sophisticated commodity traders may therefore own both operator and trader accounts. I classify account holders in three groups. *Operators* own at least one operator holding account linked to an installation with compliance obligations.[8] *Traders* are account holders of trader accounts but no such operator accounts. Finally, *administrators* are holders of administrative accounts.

Account owners provide a name and address as primary contact information that is common across their accounts owned and typically coincides with firm names and addresses. I therefore define firm name and country based on account holder name and address country, respectively. Based on installations owned by operators, I additionally link annual information on free allocations and verified emissions, aggregated to account holder level, that determine the amount of carbon permits surrendered each year. In accordance with the EU ETS compliance cycle, I merge annual information on holdings at the end of April each year. Finally, I use installation-level activity types to infer firms' main activities. Each installation is assigned one of 36 activity types such as production of coke, refining of mineral oil, or aviation activities. I then define a firm's main industry based on its installation-level activity with the highest share of total emissions.

II. Exploring Carbon Permit Holdings

II.A. Market Structure

Table A.2 includes summary statistics of permit holdings and firms' share of emissions. On average, the sample includes about 6,800 firms of which 1,200 are financial traders and the remainder are regulated operators. A majority of firms operate in the fuel combustion sector. While the sector is responsible for about two thirds of average total emissions they, on average, only hold one third of the outstanding stock of emission permits. Less than 150 firms or about 2% of operating firms are involved in the production of pig iron or steel. However, the combined sector holds 8% of total permits and received 13% of all free allowances. With close to 40%, financial traders hold a relatively large fraction of emission permits.

Figure A.1 shows aggregated monthly permit holdings by firm type. During Phase II, the stock of permit holdings increased from about 1.8bn EU ETS emission allowances (EUAs) in 2009 to about 2.9bn permits after the surrendering period in April 2013. This stark increase was the result of permit issuances based on historical emissions in years 2005-2007 and reduced permit demand due to lower output following the financial crisis in 2008. With the start of Phase III, a linear reduction factor was introduced that decreased the number of newly issued permits year on year.[9] Consequently, between May 2013 and April 2020, the stock of permits decreased by 28% to 2.1bn emission allowances. Figure A.1 also illustrates the aggregate effects of the compliance cycle on emission permit holdings. In February each year, permit holdings spike as free permits are allocated and decrease by the end of April when regulated firms surrender permits in accordance

[8] Installations are the smallest entity in the dataset representing e.g. individual power plants or factories. Compliance decisions, emission obligations and free allocations are based on installation-level activity.

[9] This annual linear reduction factor was set at 1.74% relative to a cap of 2.1 billion newly issued permits in 2013. In a series of policy changes, the annual reduction of permits has been increased to 2.2% (2021-2023), 4.3% (2024-2027), and 4.4% (2028-2030), see also Fuchs et al. (2024).

to their carbon emissions in the preceding year.[10] The gradual increase in permit stock throughout the compliance cycle reflects the issuance of permits via auctions that typically occur on 4 days per week. With about 50% financial traders own a substantially larger share of outstanding permits post 2013 than before.

Permit holdings are concentrated among few participants in the EU ETS. Table A.3 reports the average share in permit holdings for the top ten financial trading and operating firms, respectively. On average, the ten largest operators hold about 11% of total permits. ArcelorMittal—the largest steel producer in Europe and second largest worldwide— owns with an average of 2.5% the largest stock in emission permits. Energy producers RWE, Enel and PGE, who together are responsible for more than 10% of EU ETS regulated emissions, hold permits of between 1.2% and 1.5% each. Also financial traders hold large shares of emission permits. The top ten financial firms, mostly commercial banks, hold a combined share of close to 17%. With average share of 4.5%, the Commonwealth Bank of Australia is the largest holder of emission permits followed by BNP Paribas (2.7%), and the Bank of New York Mellon (2.0%). With a share in total holdings of 1.2%, Vitol S.A. is the largest commodity trader by holdings.

Operators source permits predominately from financial traders or other operators. Surprisingly, permit supply via auctions or secondary market exchanges—where large volumes of futures contracts on emission permits are traded (see Fuchs et al. (2024) for details)—appear to play only a subordinate role. Figure A.2 shows the share of operators' trading volume by counterparty and operator's level of permit holdings. For about 60% of operators' transactions volumes the counterparty is a financial trader. For operators with few holdings the counterparty is often another operator and financial traders play a lesser role than for operators with large holdings of permits. Interestingly, 90% of firms have no direct exposure to auction supply or central exchanges. While only operator firms with large holdings appear to source permits from auctions or central exchanges, its share of total trading volume is with 12% relatively low. These patterns are similar both before and after 2013 when auctioning became the default method to issue new emission permits.[11]

The value of emission permit holdings constitute a non-trivial share of firms' balance sheets. Figure A.3 shows the annual average share of emission permit and cash holdings as a share of firms' total assets across permit holding deciles. The value of emission permits on firms' balance sheets is of similar magnitude as their cash holdings. Panel (a) shows the time series average median fraction of emission permit and cash holdings for annual compliance cycles ending up until April 2018 when carbon prices were relatively low. Across deciles of firms' permit holding levels, the value of emission permits is about 0.4–0.9% of firms' total assets while the share of cash holdings ranges between 1.5 and 2.5%. Panel (b) presents the share of emission permits and cash holdings after 2018, when carbon prices increased from about 7 EUR per ton of CO2e to more than 22 EUR/tCO2e. The value of permit holdings is similar for firms with small quantities of permit

[10] Before 2013, national authorities of EU ETS member countries individually transferred free allocations and received surrendered permits. With the start of Phase III in 2013, this process was centralized at the EU Commission level. Therefore, the transition year in 2012 shows some irregularities in the form of earlier allocations.

[11] Participation in auctions is highly concentrated. In 2023, only 10 firms purchased 90% of permits issued via auctions and 80% were purchased by financial traders (ESMA, 2024).

holdings after 2018. In contrast, holders of larger quantities appear to replace cash holdings with holdings of emission permits. The value of emission permits of large permit holders doubled from about 0.7% of total assets before 2018 to 1.4% after 2018. At the same time, their cash holdings reduced from 2.7% of total assets to 1.4%.

II.B. Excess Permit Holdings

Next, I turn to explore the level of operators' permit holdings relative to their annual emission levels, i.e. the quantity of permit obligations that regulated firms need to surrender each year. Operators may sell any permits in excess of their compliance obligations or retain them for future use. Regulated firms may hold excess permits to hedge against shocks to future permit prices (Hahn and Stavins, 2011; Baldursson and von der Fehr, 2004), for example due to changes in abatement cost or policy changes in the supply of future permits, because of financial frictions such as firms' capital constraints (N'Gatta et al., 2023), or market frictions such as transaction costs.

I define excess holdings at the firm-year level as the quantity of emission permit holdings just after the surrendering of permit obligations at the end of each compliance cycle divided by the the amount of surrendered emissions. More specifically, excess holdings in annual compliance cycle τ are the sum of permits held at the beginning of the period $H_{i,\tau,0}$, the net amount traded $NetTrade_{i,\tau}$, and the quantities received from $Allocation_{i,\tau}$ and transferred to $Surrender_{i,\tau}$ the regulator divided by the amount of permits surrendered in the same cycle:[12]

$$EH_{i,\tau} = \frac{H_{i,\tau,0} + NetTrade_{i,\tau} + Allocation_{i,\tau} - Surrender_{i,\tau}}{Surrender_{i,\tau}} \tag{2}$$

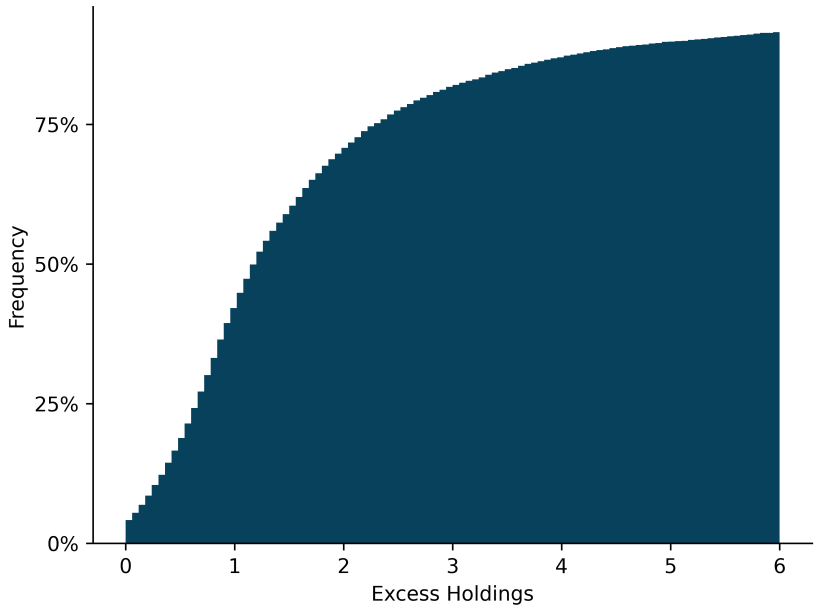
There is large cross-sectional variation in regulated firms' excess permit holdings. Figure 1 shows the distribution of annual average excess holdings. About a quarter of firms keep few excess holdings of less than 1. That is, at the end of their compliance cycle they hold an insufficient number of permits—abstracting from future free allocations—to cover future emissions of the same level such that they will either need to buy permits on the market or reduce future emissions. In fact, almost 4% of firms retain zero precautionary emission permits at the end of the compliance cycle as they often acquire only the number of permits required to fulfill their current emission obligations.

Many operators, however, hold large quantities of excess permits. In an average year, the median firm holds precautionary permits of 1.25, sufficient to cover emissions of the same level in the subsequent year without relying on free allocations or market purchases of permits. With precautionary permit holdings above 2, the top 25% of firms retain emission permits that are multiples of their current emission levels.

One potential reason why firms may keep large excess holdings may be that they operate in sectors where emissions are technologically difficult to abate. However, the large cross-sectional variation in excess holdings and often large quantities of excess permits also persist within indus-

[12] In rare cases, regulated firms surrender their carbon permits only in the first week of May, potentially due to weekends or holidays. Defining the end of a compliance cycle as the end of April or the first week of May does not affect any results.

Figure 1: Excess Permit Holdings



Note: Cumulative distribution of annual average excess permit holdings. Excess permit holdings are the level of emission permit holdings at the end of the compliance cycle, i.e. after surrendering the annual permit obligations, divided by the amount of permits surrendered in the same year.

tries. Table A.5 reports excess permit holdings by main activity of the regulated firm. Among the largest 10 industries, firms involved in the production of bulk chemicals retain the highest levels of precautionary holdings with median excess holdings of 1.75. With an inter-quartile range of 0.90 to 4.02, however, also the within-industry variation is large. While the median firm in the aviation industry holds with a rate of 0.28 much fewer excess permits, the within-industry range of excess permits holdings is similarly wide (inter-quartile range of 0.05 to 0.77).

II.C. Determinants of excess permit holdings

Why do regulated firms hold large quantities of excess permits? Operators are able to trade emission permits on large, relatively liquid permit markets to cover their emission obligations or sell any excess permits. Thus, the large variation of excess permit holdings—even present within granular industry activities—and low trading participation is puzzling.

In the following part of this section, I explore the nature of firms that hold large quantities of excess emission permits. The large variation in excess holdings may be explained by firms' uncertainty about the future cost of abatement, for example via innovations in decarbonization technology, financial frictions such as constraints on liquidity provision or capital access or other non-financial motives such as the smoothing of reported earnings. N'Gatta et al. (2023) indeed find that firms are more likely to sell emission permits when they face liquidity constraints or lower earnings consistent with a motive to smooth accounting losses. Alternatively, market frictions, such as transaction costs or uncertainty about future permit prices may withhold firms from

realizing trading profits by selling excess permits on the market. If excess permits stem from free allocations, such market frictions may point to a violation of the independence property (Hahn and Stavins, 2011). Modeling a market of tradable emission permits, Baldursson and von der Fehr (2004) show that risk averse firms facing uncertainty about future abatement cost are less likely to sell initial permit allocations as they hedge uncertainty by retaining higher levels of emission permits. Firms with ex-ante lower levels of emission permits, on the other hand, hedge uncertainty by investing in decarbonization. As a result, net sellers invest less in emission reduction than net buyers.

To explore the determinants of firms' excess holdings, I collect firm-level financial and emission characteristics to account for firms' exposure to financial constraints, incentives for performance-smoothing as well as their emission profile and free permit allocations. In a panel setting, I regress firm i's excess holdings at the end of each annual compliance cycle τ on candidate explanatory characteristics of the same year:

$$EH_{i,\tau} = Emission_{i,\tau} + Financial_{i,\tau} + \gamma_\tau * \psi_{ind} + \epsilon_{i,\tau} \tag{3}$$

where $Emission_{i,\tau}$ is a vector of firms' emission characteristics including current and total change of emissions relative to emission levels in the previous year and the median of the first three years the firm occurs in the sample, respectively. I also include the log of total emissions, the rolling 5-year standard deviation of emissions and the quantity of free allocations as a share of total emissions in the same year. $Financial_{i,\tau}$ collects firms' balance sheet characteristics including liquidity, leverage, Whited and Wu (2006)'s measure of financial constraints, profitability, the log of total assets, and emission intensity as the ratio of emission levels to total assets.[13] Table A.1 provides definitions and details on all variables. To control for time-varying cost of emission abatement, I additionally include Year*Industry fixed effects where γ_τ denotes annual compliance cycle from May to end of April in each calendar year and ψ_{ind} represents granular industry activity levels.

Table I reports Shorrocks-Shapley (2013) decomposed values of adjusted R-squares estimated according to Equation (3). By far the largest determinant of excess permit holdings is the share of freely allocated permits relative to the firm's emission level in the same year. Table A.6 in the Appendix presents estimated regression coefficients reporting a strong positive relationship between excess permit holdings and free permit allocations. Other candidate determinants of excess holdings play a much lesser role. Firms' financial characteristics explain less than 3% of the variation in excess permit holdings. Firms with larger levels of emissions appear to hold somewhat smaller excess permits while larger firms, in terms of total assets, exhibit higher excess holdings. In line with N'Gatta et al. (2023), I find financially constrained firms hold higher levels of excess permits. However, given the positive coefficients for measures of liquidity and profitability, I find no effect consistent with smoothing of accounting losses or liquidity provision.[14]

[13] I match financial data based on the fiscal year definition of Compustat. Thus, firms with reporting period ends from January through May in a given year are matched to the same compliance cycle as firms with reporting periods that end from June to December in the previous year.

[14] N'Gatta et al. (2023) find a negative relationship between firms liquid assets or accounting losses and their likelihood to sell emission permit which may correspond to lower permit holdings. However, their sample period is with years from

Table I: Determinants of Excess Permit Holdings

Dependend variable:	Shapley Value [%]	
Excess Holdings	(1)	(2)
Free Allocation	22.43	22.32
Log Emissions	6.90	9.59
Total Emission Change	0.94	0.96
Emission Volatility	0.71	0.70
Current Emission Change	0.19	0.07
Financial Constraints		0.90
Emission Intensity		0.87
Total Assets		0.81
Profitability		0.23
Leverage		0.10
Liquidity		0.02
Industry x Year FE	4.25	2.90
R2-Adjusted	35.41	39.47
N	51,391	18,457

Note: Shorrocks-Shapley (2013) decomposition of adjusted R-squared from a panel regression specified in Equation (3). Shapley values represent the decomposition of the adjusted R-squared by regressors. All values are in percent. All variables are defined in Table A.1 and winsorized at the 1st and 99th percentiles. Estimates in column (1) include emission characteristics; column (2) adds financial characteristics. Corresponding regression coefficients are reported in Table A.6 in columns (3) and (6), respectively. The sample period covers compliance cycles ending in 2009 through 2020.

The strong positive correlation between firms' free allocation and excess permit holdings is surprising. As free allocations of permits are the main determinant of firms' excess holdings, the equilibrium allocation of permits may not be independent from an initial allocation of free permits potentially deviating from the joint cost minimum derived by Montgomery (1972).

The independence property is based on the central assumption that regulated firms take advantage of trading gains by selling any excess permits. In an efficient market, the equilibrium allocation, therefore, depends solely on firms' marginal abatement cost curves (Hahn and Stavins, 2011). The fact that free permit allocations explain large parts of firms' excess permit holdings, indicates that market frictions may prevent firms from selling their surplus allowances.

Exploring the trading activity in the EU ETS, I find the overall trading participation in the permit market is low, in particular for firms holding large quantities of excess permits. I calculate the trading turnover at the firm-level as the ratio of annual trading volume to median permit holding in the same year. Table A.4 summarizes firms' aggregate trading turnover by decile of permit holdings and firm type. Perhaps unsurprisingly, financial traders—in particular those with large holdings—trade much larger volumes. With median annual trading volumes up to 520% relative to their holdings, the trading turnover of financial traders is often an order of magnitude higher than that operating firms of similar holding levels. In contrast, many operators hardly trade. The average annual trading turnover of the bottom quarter of firms is close to

2013 to 2017 much shorter. In addition, they also only consider firms' contemporaneous transactions ignoring their ex ante permit holdings and therefore their capacity to sell.

zero across all holding deciles. With exception of operating firms with small holdings, even the median annual trading volume ranges between 5% in the 5th permit holding decile and 39% for operators with large holdings. The low trading volumes of operators are predominately driven by net sellers of emission permits where net sellers (net buyers) are defined as operators with end-of-year precautionary permit holdings equal or above (below) the sample median of 1.25. Across deciles of permit holdings, net sellers trade consistently less than net permit buyers. The difference in trading turnover is often an order of magnitude. For example, the median trading turnover of large net buyers is 73% while the median net seller only trades 17% of their permit holdings in an average year.

III. Excess Permit Holdings and Price Uncertainty

Why do regulated firms not sell their excess emission permits? In the following section, I explore whether uncertainty about future permit prices affects regulated firms' trading behavior. In times of high carbon price uncertainty, firms may increase their permit holdings as a precautionary hedging motive against future shocks to permit supply or decarbonization costs. Hence, uncertainty about future carbon prices may inhibit risk averse operators with large excess permit holdings (henceforth *net sellers*) from selling permits on the market.

Studying the oil market, Gao et al. (2022) find that an increase in oil price uncertainty is associated with an increase in oil inventories. There also exists theoretical and experimental evidence that uncertainty about the future cost of decarbonization can lower trading volume and net sellers' propensity to sell allowances in emission trading schemes. While net sellers hedge price uncertainty by banking emission permits, net buyers may overinvest in decarbonization activities (Yoon et al., 2024; Betz and Gunnthorsdottir, 2009; Baldursson and von der Fehr, 2004).

Fuchs et al. (2024) develop a market-based index of carbon price volatility (henceforth Carbon VIX) from option prices on emission permits in the EU ETS. They show that expected carbon price volatility is substantially higher than for other commodities—in particular oil prices—and exhibits large variation over time. The high uncertainty about future carbon prices may therefore have substantial implications for firms' trading behavior. I use the Carbon VIX to measure permit price uncertainty at the monthly level from September 2013 through December 2022.[15]

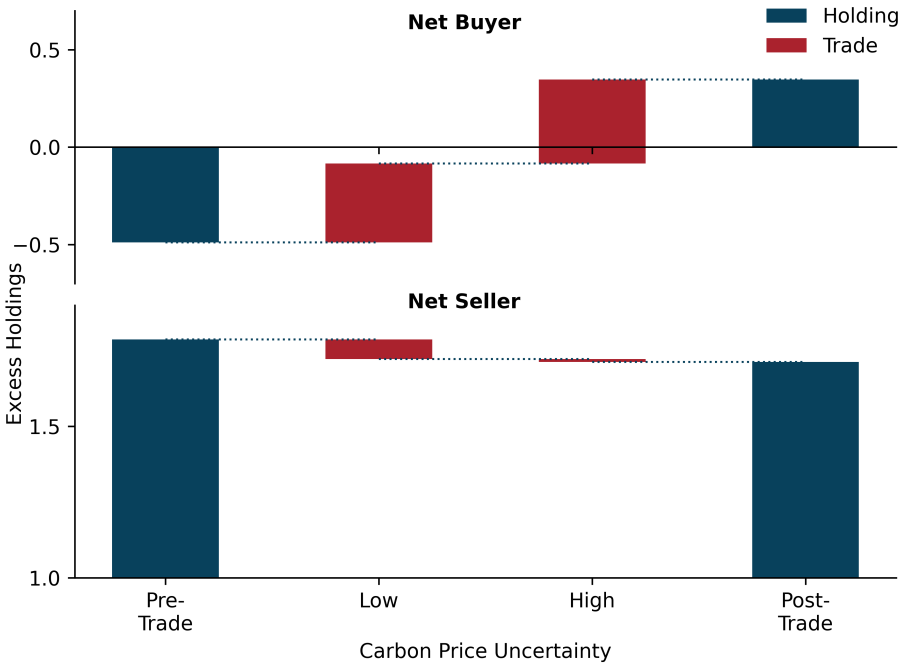
Figure 2 illustrates the trading patterns of both net buyers and net sellers at the aggregate level. Net buyers need to buy permits on the market in order to meet their end-of-year compliance obligations.[16] At the beginning of each compliance year and before any trading, net buyers hold an average quantity of emission permits that is about 50% (or 560 million emission permits) short of their emission obligations for the same year. On aggregate, net buyers purchase about 40% of their annual emission permit obligations, both in months of low and high carbon price uncertainty. At the start of the average compliance year, net sellers already hold permits that

[15]The Carbon VIX is available for download at www.carbonvix.org.

[16]I define net buyers as firms holding permits of 125% or less of their future emission obligations before any trading (i.e. the sum of permit holdings at the beginning of each compliance period and the ex-ante known quantity of free permit allocations divided by the level of verified emissions in that period). This threshold corresponds to the median level of excess permit holdings; see Section II.B.

exceed their aggregate compliance obligations of on average 760 million emission permits by 178%. Although net sellers have large excess holdings and therefore a large capacity to sell, they do so only in times of low carbon price uncertainty. In months where expected carbon price volatility is below its median, net sellers sell about 7% of the same years' emission obligations. In contrast, during months of high permit price uncertainty, net sellers sell on average less than 1% of their emission obligations. The imbalance in permit supply from net sellers and permit demand from net buyers is compensated via frequent auctions of emission permits and inventories of financial liquidity providers in times of high carbon price uncertainty.

Figure 2: Trading and Carbon Price Uncertainty



Note: Average aggregate excess holdings of net sellers and net buyers as a percentage of end-of-year emission obligations. Excess holdings are the sum of permit holdings at the beginning of each compliance period and the ex-ante known quantity of free permit allocations in excess of the emission obligations of the same year. Net sellers (net buyers) are firms with pre-trade excess holdings—including ex ante determined free allowances—of more (equal to or less) than 125% of their end-of-year emission obligations. The left- (right-) hand blue bar shows excess holdings before (after) any trading. The red bars show the average aggregate amount traded during months of high (low) carbon price uncertainty at or above (below) the time-series median level of the Carbon VIX.

To systematically assess the relationship of carbon price uncertainty and net sellers' trading behavior, I first define the change in firms' permit holdings similar to Baumeister and Hamilton (2023):[17]

$$\delta H_{i,t} = \frac{H_{i,t} - H_{i,t-1}}{0.5(H_{i,t} + H_{i,t-1})} \tag{4}$$

I then follow Gao et al. (2022) and estimate a predictive set of panel regressions of the form:

[17]Equation (4) can be seen as a first order Taylor expansion to $log(H_{i,t}) - log(H_{i,t-1})$ which is less sensitive to large changes in holdings as it is bound between ±2 for all values of $H_{i,t}$ and $H_{i,t-1}$. Changes in holdings only include transactions among regulated and financial firms and exclude transactions where one counterparty involves an administrative account that stem, for example, from the allocation of free allowances or the surrendering of permits.

$$\begin{aligned}\delta H_{i,t+1} = \beta_1 \Delta CarbonVIX_t \times \mathbb{1}\{NetSeller\} \\ + X_{i,t} \times \mathbb{1}\{NetSeller\} + \psi_i + \gamma_t + \epsilon_{i,t}\end{aligned} \tag{5}$$

where $\Delta CarbonVIX_t$ is the monthly change in the CarbonVIX. To control for the demand of net buyers who face tight constraints to purchase emission permits each year in April, I add an interaction term $\mathbb{1}\{NetSeller\}$ that takes the value of one if the regulated firm is a net seller. Hence, β_1 can be interpreted as the increase in the gap of excess holdings between net buyers and net sellers conditional on the change in the CarbonVIX. ψ_i and γ_t denote firm and month fixed effects, respecively. $X_{i,t}$ collects controls that may affect firms' demand for carbon permits such as monthly market characteristics including oil price returns and the oil VIX as well as the return and VIX of the EU market index. I also control for transaction costs as proxied by the bid-ask spread of the carbon price. Finally, I include annual firm-characteristics including the log emission level, the rolling 5-year emission volatility, the firm's annual and total emission change and the percentage of free allowances received relative to the firms' realized emissions in the same year. All variables are winsorized at the 1st and 99th percentile. Table A.7 provides summary statistics.

Table II: Excess Permit Holdings and Price Uncertainty

	δH_{t+1}					
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon VIX Changes	-0.030	0.164***	0.157***	0.284***	0.291***	0.249***
× Net Seller	(0.040)	(0.050)	(0.051)	(0.051)	(0.051)	(0.051)
Carbon Price Return		0.194***	0.182***	0.184***	0.194***	0.168***
× Net Seller		(0.028)	(0.028)	(0.028)	(0.028)	(0.028)
Market Characteristics	No	No	No	Yes	Yes	Yes
Transaction Cost	No	No	No	No	Yes	Yes
Firm Characteristics	No	No	No	No	No	Yes
Date	Yes	Yes	No	No	No	No
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Net Seller	Yes	Yes	Yes	Yes	Yes	Yes
Date x Industry	No	No	Yes	Yes	Yes	Yes
Date x Country	No	No	Yes	Yes	Yes	Yes
Observations	419,381	419,381	418,221	418,221	418,221	374,033
R2-Adjusted	0.12	0.13	0.14	0.14	0.14	0.14

Note: Regression estimates of Equation (5). The dependent variable is one-month-ahead changes in emission permit holdings. The main independent variable is monthly changes in Carbon VIX interacted with an indicator of net sellers. Net sellers (net buyers) are firms with pre-trade excess holdings——including ex ante determined free allowances——of more (equal to or less) than 125% of their end-of-year emission obligations. The sample period is from 2013.09 to 2020.04. All variables are winsorized at the 1st and 99th percentile and defined in A.1. Standard errors are clustered at the *firm* and *month x industry x country* levels. *p<.1; **p<.05; ***p<.01

Table II presents the estimated results of Equation (5). Following months of higher carbon price uncertainty, net sellers sell significantly less carbon allowances. Conversely, after months in which carbon price uncertainty decreases firms holding high quantities of excess permits sell significantly more emission allowances. This effect is not explained by market or firm characteristics, transaction cost, or time-varying industry and country characteristics. In the most restrictive specification, a one standard deviation (7.69 ppt.) decline in carbon price uncertainty predicts an average annual decrease of net sellers' permit holdings by 3% (0.25% x 12). As net sellers sell only 2.6% (0.22% x 12) during an average year, this effect is economically substantial. Net sellers also sell less emission permits after months of carbon price increases. Although, with an annual average 2% (0.17% x 12) decrease in sales for a one standard deviation (13.5%) increase in carbon prices, this effect is smaller than that of carbon price uncertainty.

The negative effect of carbon price uncertainty on net sellers emission permit sales is robust to alternative definitions of net sellers and for different sub-samples. Columns (1) and (2) of Table A.8 show that the effect is similar if the threshold for defining net sellers is set at 100% of firms' pre-trade permit holdings relative to their end-of-year emission obligations. Columns (3) and (4) exclude months of firms' increases in emission permits, providing evidence that it is net sellers *sales* of emission permits that significantly decrease with higher carbon price uncertainty. Finally, columns (5) and (6) show that the effect is quantitatively similar after including changes in permit holdings of financial traders.

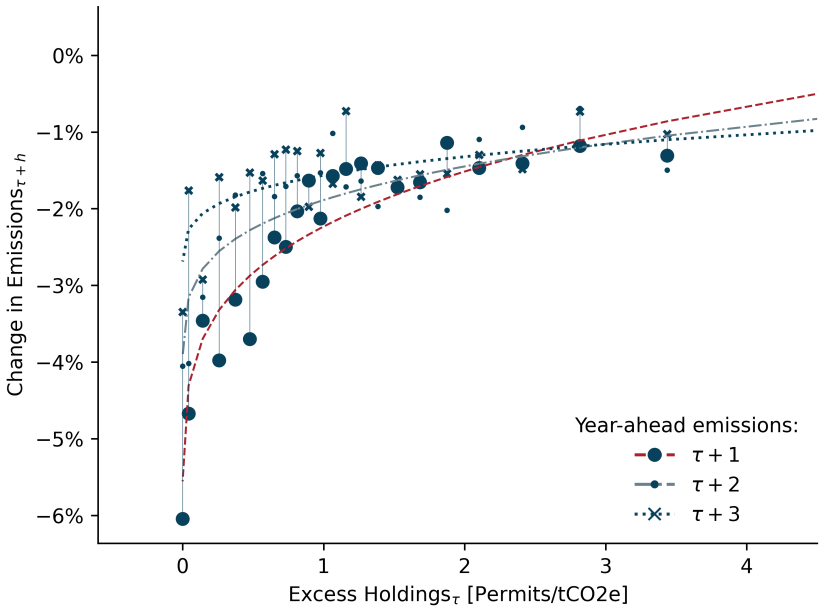
IV. Excess Permit Holdings and Carbon Emissions

Does the quantity of emission permits firms hold affect their future decarbonization outcomes? Generally, firms' decarbonization decisions depend on their expected marginal abatement cost and the future price of carbon emissions. If for certain firms the cost of emission abatement exceeds the expected price of carbon permits, they may purchase permits from firms whose abatement cost are below the expected carbon price and investment in reducing emissions is profitable. Therefore, the initial level of permit holdings should impact firms' future decarbonization outcomes only via differences in abatement costs. Baldursson and von der Fehr (2004), however, theoretically show that net sellers of emission permits under-invest in emission reduction while net buyers over-invest in decarbonization given that firms are risk averse and permit prices are subject to uncertainty. In other words, firms with large excess permit holdings may hedge carbon price uncertainty by selling fewer emission permits while firms holding few excess carbon permits hedge carbon price uncertainty by reducing carbon emissions and thereby their exposure to emission permit prices.

Figure 3 provides a first exploration and plots firms' excess permit holdings on one, two, and three year-ahead emission changes. Firms with few excess permit holdings in a given year exhibit substantially higher emission reduction rates during subsequent years than firms holding large quantities of excess permits. This effect is strongest for one-year ahead decarbonization rates and becomes weaker for emission changes in the more distant future. Notably, firms with excess permit holdings below 1—i.e. firms who need to purchase emission permits on the market to meet

their end-of-year permit obligations—account for most reductions in future carbon emissions.[18] In contrast, firms holding emission permits exceeding their permit obligations show substantially lower emission reduction rates. While this pattern is consistent with predictions of Baldursson and von der Fehr (2004), the large variation in emission reductions may be driven by differences in firms' marginal abatement cost or other determinants such as firms' emission levels or past achievements in emission reductions.

Figure 3: Excess Permit Holdings and Future Carbon Emissions



Note: This figure plots one, two, and three year-ahead annual average changes in median carbon emissions on annual average percentiles of excess permit holdings. Excess permit holdings are the level of emission permit holdings at the end of the compliance cycle, i.e. after surrendering the annual permit obligations, divided by the amount of permits surrendered in the same year. The sample period overs compliance cycles ending in 2009 through 2020.

To control for firms' abatement cost and other firm characteristics, I estimate the following panel regression at the annual level:

$$\Delta Emissions_{i,\tau+1} = \beta_1 logEH_{i,\tau} + X_{i,t} + \psi_{ind} \times \gamma_\tau + \epsilon_{i,\tau} \tag{6}$$

where $logEH_{i,\tau}$ is the logarithm of one plus firm's i excess permit holdings at the end of compliance cycle τ and $\Delta Emissions_{i,\tau+1}$ is the firm' relative change in the one-year-ahead carbon emissions. To proxy for firms' marginal abatement cost, I include industry by year fixed effects where industry codes are based on 35 granular classifications of firms' main activities such as the manufacturing of ceramics, the production of pig iron or steel, and the manufacturing of glass. Regulated firms' future emission reduction may depend on their past emission path. Hence,

[18] Regulated firms holding fewer excess holdings tend to be larger, see Table I.

$X_{i,t}$ collects additional controls including firm's i emission change in compliance year τ, its total emission change, as well as the 5-year rolling standard deviation of emissions. In addition, I control for the level of firms' carbon emissions as well as their share of free permit allocation.

Table III presents the regression estimates. Firms holding larger quantities of excess emission permits have significantly lower reductions in carbon emissions in the subsequent year. This relationship holds also after controlling for firms' abatement cost via industry fixed effects as well as within firms, i.e. after absorbing firm specific characteristics. A 10% increase in firms' excess permit holdings is associated with about 0.4–0.5 percentage points lower decrease in carbon emissions. Given that the mean decrease in carbon emissions is 1.2 %, this effect is economically substantial. Interestingly, the share of firms' free permit allocations appears to be unrelated to firms' future emission reductions consistent with findings of Zaklan (2023).

The higher emission reduction rates for firms with low excess permit holdings may be a rational response to mitigate uncertainty about future carbon cost as in the model of Baldursson and von der Fehr (2004). An alternative explanation may be that firms with larger quantities of excess holdings fail to recognize the opportunity cost of making trading profits or are averse to selling emission permits that are already in their possession. This endowment effect may lead firms to retain excess permits to prevent losses from future states where the permit supply is more scarce increasing the price for which they are willing to sell Yoon et al. (2024). As a result, the constraint for emission reductions is tighter for firms with fewer excess permit holdings.

V. Conclusion

The reduction of aggregate carbon emissions has become a key policy objective ti mitigate adverse effects of climate change. The pricing of carbon emissions to incentivize firms to decarbonize their operations is a common policy tool often implemented via tradable emission permits in cap-and-trade systems. The market mechanism of such systems is a key feature that allows firms to decarbonize cost-efficiently by either reducing their emissions or purchasing permits to emit carbon from firms whose decarbonization costs are lower. This paper documents new evidence of firms' trading behavior and decarbonization activities in the EU Emission Trading System, the world's oldest and largest cap-and-trade-system. I construct a novel dataset of firm-level holdings in emission permits that allows to study how firms trade emission permits and how the equilibrium allocation of emission permits interacts with permit prices and firms' decarbonization outcomes. My main findings show that many firms hold large quantities of excess permits relative to their emission levels. Firms refrain from selling excess permits to hedge shocks to future carbon prices. Complementing theoretical predictions of earlier work, I empricially find lower trading activity and smaller decarbonization rates for firms with high levels of precautionary permit holdings.

These findings have important implications for policy makers. Uncertainty about carbon prices may lead to deviations from cost-optimal decarbonization as holders of excess allowances refrain from selling emission permits. Several measures may limit these frictions and promote trading participation. The introduction of (long-dated) maturities for emission permits, a swifter switch from free permit allocation to allocations via auctions, or a reduction in carbon price uncertainty—

Table III: Excess Permit Holdings and Future Carbon Emissions

	ΔEmissions$_{t+1}$					
	(1)	(2)	(3)	(4)	(5)	(6)
Log Excess Holdings	0.035***	0.036***	0.036***	0.030***	0.050***	0.046***
	(0.005)	(0.005)	(0.004)	(0.007)	(0.007)	(0.008)
Log Emissions				-0.332***	-0.289***	-0.277***
				(0.016)	(0.016)	(0.024)
Current Emission Change					0.030***	0.030***
					(0.007)	(0.010)
Emission Volatility						-0.000*
						(0.000)
Free Allocation Share						0.000
						(0.000)
Total Emission Change						-0.041**
						(0.016)
Year	No	Yes	No	No	No	No
Industry	No	Yes	No	No	No	No
Firm	No	No	No	Yes	Yes	Yes
Country	No	No	No	Yes	Yes	Yes
Year x Industry	No	No	Yes	Yes	Yes	Yes
Year x Country	No	No	Yes	Yes	Yes	Yes
Observations	59,005	59,004	58,890	58,545	56,913	46,264
R2-Adjusted	0.01	0.04	0.09	0.25	0.23	0.23

Note: Regression estimates of Equation (6). The dependent variable is the relative change in one-year-ahead carbon emissions. The main independent variable is the logarithm of excess permit holdings plus one at the end of compliance cycle. Excess permit holdings are the level of emission permit holdings at the end of the compliance cycle, i.e. after surrendering the annual permit obligations, divided by the amount of permits surrendered in the same year. To avoid extreme outliers, I remove firm-year observations of the bottom emission quintile. All variables are winzorized at the 1st and 99th percentile and defined in Table A.1. The sample period overs compliance cycles ending in years 2009 to 2020. Standard errors are clustered at the *firm* and *year x industry x country* levels. *p<.1; **p<.05; ***p<.01

for example via price collars or clearer forward guidance on future policy changes.

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Carbon Permit Holdings

Appendix

Section A.1 contains further details on the construction of carbon permit holdings.

A.1. Constructing Carbon Permit Holdings: Additions

A.1.A. Recovering Missing Transactions

I identify and fill missing counterparty information for transactions that occur in Phase II, between 2008 and 2012, and affect about 20% of trading volumes during this period. Based on previous data vintages and a matching algorithm of account identifiers, I am able to restore 99% of missing transactions.[19] In addition, I detect and delete redundant transactions for the purpose of banking and wrong cancellation of allocated allowances (Supplementary transaction types 33 and 34, and 93). In addition, I identify administrative *transition* accounts which are used as intermediary accounts for the transferal of permits between EU ETS phases I and II. As the transaction data only include incoming transactions but not outgoing, I remove the the first leg of the transactions with unspecified transaction type (0).[20]

A.1.B. Linking Accounts Across Phases

Generally, account ownership is consistent over time. However, during the transition from EU ETS Phase II to III in 2013, accounts in the public registries had to close and re-open with new accounts. Abrell (2024) links phase II accounts to current accounts using a matching algorithm based on account name and account owner, surrendering transfers and allocation transactions. I supplement this approach by detecting phase II accounts with positive permit holdings and link it to successor accounts based on their association with carbon emitting installations. I group account holders, if a phase II account holder's installations is linked to multiple successor account holders via their installations. For every phase II and successor account holder, I prefer the associated information such as account name and country of the more recent successor account.

A.1.C. Identifying Account Owners

I identify common account ownership or firms based on three sets of criteria in addition to those in Abrell (2024). First, accounts belong to the same firm if they provided the same account holder name and registered in the same country. Second, I merge accounts with the same Bureau van Dijk *bvdId* identifier as provided by Letout (2021). Lastly, I manually identify and match accounts of about 50 large conglomerates or financial traders based on their name, country and Bureau van Dijk ownership information. For each account owner identified, I aggregate verified emissions, permit holdings, and free permit allocation the the account owner level.

[19] In an updated version, Abrell (2024) provides the restored missing data based on a similar matching algorithm.

[20] These intermediary accounts only affects few transactions in Poland, Estonia, Hungary, Norway, Latvia, and Lithuania but would lead to negative holdings due to missing outgoing transactions.

Table A.1: Variable definitions

Variable	Definition	Unit	Source
Panel A: Firm Characteristics			
Emissions	Annual verified emissions	tCO2e	EU TL
Free allocation	Total free allocation (incl. new entrance allocations) as a share of emissions	%	EU TL
Emission Volatility	Rolling 5-year standard deviation of emissions		EU TL
Total Emission Change	Percent change in emissions compared to first year in sample		EU TL
Current Emission Change	Percent change in emissions compared to previous year		EU TL
Total Assets	Total Assets	EUR	Orbis
Liquidity	Cash and cash equivalents divided by current assets		Orbis
Leverage	Long term debt divided by total assets		Orbis
Emission Intensity	Emissions divided by total assets	tCO2e/EUR	Orbis, EU ETL
Profitability	EBT divided by total assets		Orbis
Financial Constraints	-.0091 * Cashflow/Total Assets + 0.021 * Leverage + 0.044 * Log Total Assets + 0.102 * Industry Sales Growth - 0.035 * Sales Growth, see Whited and Wu (2006)		Orbis
Panel B: Market Characteristics			
Carbon VIX	Option implied 120-day expected carbon price volatility, see Fuchs et al. (2024)	%	carbonvix.org
Carbon Price	Settlement price of EUA December futures front contract	EUR	carbonvix.org
Bid-ask-spread	Difference in bid and ask divided by their mean		Refinitiv Eikon
Oil Price	Settlement price of Brent crude oil futures front contract	EUR	Bloomberg
Oil VIX	OVX index based on crude Oil ETF	%	Bloomberg
Market Index	Total return index of Euro Stoxx 50	EUR	Bloomberg
Market VIX	VSTOXX index based on Euro Stoxx 50	%	Bloomberg

Table A.2: Summary Statistics

Firm Type	Holdings		Emissions	Free Alloc.	Firms
Industry	[mio]	[%]	[%]	[%]	[#]
Traders:					
	1,107.47	38.50	0.00	0.00	1,193
Operators:					
Combustion of fuels	955.91	33.23	64.62	48.01	2,913
Production of pig iron or steel	231.34	8.04	7.48	13.02	136
Production of cement clinker	135.78	4.72	6.48	10.93	103
Refining of mineral oil	114.17	3.97	6.02	7.62	73
Combustion installations with a rated thermal input exceeding 20 MW	46.19	1.61	2.94	2.71	379
Production of lime, or calcination of dolomite/magnesite	38.47	1.34	1.41	2.15	119
Production of bulk chemicals	34.52	1.20	1.66	2.46	94
Aircraft operator activities	29.73	1.03	2.18	2.11	132
Mineral oil refineries	29.32	1.02	0.93	1.21	4
Production of paper or cardboard	26.43	0.92	1.06	1.64	353
Manufacture of glass	21.88	0.76	0.98	1.39	223
Manufacture of ceramics	17.71	0.62	0.59	1.04	473
Other	87.96	3.06	3.66	5.71	635
Total	2,876.88	100.00	100.00	100.00	6,829

Note: Holdings are annual averages of median monthly permit holdings. Emissions and free allocation are the share of annual average surrendered and freely allocated permits, respectively. Firms are the average number of firms in the sample. All values are by firm type and operator industry. The sample period is May 2008 to April 2020.

Table A.3: Top Permit Holders

Firm Type	Industry	Holdings		Emissions	Free Alloc.
Name		[mio]	[%]	[%]	[%]
Arcelormittal	Production of pig iron or steel	94.41	2.51	2.18	3.93
RWE AG	Combustion of fuels	56.37	1.50	6.22	2.41
Enel S.p.A.	Combustion of fuels	45.25	1.20	1.69	1.04
PGE Energia Ciepła	Combustion of fuels	43.29	1.15	3.53	2.97
Vattenfall	Combustion of fuels	29.49	0.78	0.87	0.44
Salzgitter Flachstahl GmbH	Production of pig iron or steel	28.90	0.77	0.39	0.53
BASF SE	Combustion of fuels	28.76	0.76	0.32	0.43
EDF Energy	Combustion of fuels	28.63	0.76	1.35	0.79
ENDESA S.A.	Combustion of fuels	25.09	0.67	1.04	0.51
CEZ, a. s.	Combustion of fuels	24.86	0.66	0.81	0.89
Total Operators:		405.07	10.76	18.40	13.95
Commonwealth Bank of Australia		168.64	4.48	0	0
BNP Paribas		100.63	2.67	0	0
The Bank of New York Mellon		76.28	2.03	0	0
UniCredit Bank		60.42	1.60	0	0
JP Morgan		47.74	1.27	0	0
Bayerische Landesbank		47.14	1.25	0	0
Vitol S.A.		46.10	1.22	0	0
Citigroup		45.14	1.20	0	0
Commerzbank AG		36.17	0.96	0	0
Total Traders:		875.63	16.68		
Total:		1,280.70	27.44	18.40	13.95

Note: Top 10 permit holders by firm type. Holdings are annual averages of median monthly permit holdings. Emissions and free allocation are the share of annual average surrendered and freely allocated permits, respectively. All values are by firm type and operator industry. The sample period is May 2008 to April 2020.

Table A.4: Turnover

	Trading Turnover											
	Trader			Operator								
Holding				Total			Net Buyer			Net Seller		
Decile	P25	P50	P75	P25	P50	P75	P25	P50	P75	P25	P50	P75
1	0.00	0.71	15.33	0.15	2.65	35.78	0.30	4.26	54.56	0.00	0.16	0.84
2	0.00	0.21	2.63	0.04	0.59	3.68	0.12	0.86	5.37	0.00	0.02	0.80
3	0.00	0.32	3.67	0.00	0.17	1.30	0.02	0.47	2.08	0.00	0.00	0.34
4	0.00	0.47	2.76	0.00	0.05	0.79	0.00	0.26	1.22	0.00	0.00	0.28
5	0.01	0.70	5.76	0.00	0.06	0.62	0.00	0.23	0.98	0.00	0.00	0.25
6	0.07	0.88	11.02	0.00	0.05	0.60	0.01	0.22	1.03	0.00	0.01	0.28
7	0.03	0.84	5.61	0.00	0.07	0.61	0.01	0.31	1.15	0.00	0.02	0.28
8	0.23	1.81	22.78	0.00	0.13	0.67	0.03	0.35	1.13	0.00	0.03	0.34
9	0.82	5.14	23.89	0.01	0.19	0.77	0.07	0.44	1.41	0.00	0.08	0.40
10	1.14	5.22	22.21	0.05	0.39	1.41	0.21	0.73	3.02	0.02	0.17	0.58

Note: Annual averages of firm-level 25th, 50th, and 75th percentiles of turnover by decile of permit holdings. Trading turnover is calculated at the firm-level as the ratio of annual trading volume to median permit holding in the same year. Trading volumes account for trades where the counterparty is either an operator or trader and excludes transactions with administrators for example for surrendering purposes. Net buyers (net sellers) are operators with end-of-year excess permit holdings below (equal or above) the sample median of 1.25. The sample period is May 2008 to April 2020.

Table A.5: Excess Permit Holdings

Industry	N	Mean	Std	P25	P50	P75
Combustion of fuels	3,243	2.05	4.72	0.64	1.12	2.06
Combustion installations with a rated thermal input exceeding 20 MW	634	1.88	2.39	0.80	1.24	2.00
Manufacture of ceramics	622	1.87	2.12	0.88	1.39	2.23
Production of paper or cardboard	368	2.09	3.78	0.75	1.13	1.88
Manufacture of glass	241	1.46	1.29	0.80	1.15	1.78
Aircraft operator activities	205	2.08	8.16	0.05	0.28	0.77
Production of pig iron or steel	145	2.05	1.58	1.08	1.71	2.65
Production or processing of ferrous metals	135	1.52	1.29	0.78	1.16	2.02
Production of lime, or calcination of dolomite/magnesite	131	1.90	1.54	1.00	1.55	2.24
Production of bulk chemicals	124	5.19	16.50	0.90	1.75	4.02

Note: Annual average excess permit holdings by largest ten industries. Excess holdings are the quantity of emission permit holdings at the end of each compliance cycle, i.e. after surrendering the annual permit obligations, divided by the amount of permits surrendered in the same year. Industry is the main activity type that accounts for the largest share of the firm's emissions where activity types are provided by the EU Commission. To avoid outliers, I remove firms in the lowest emission decile.

Table A.6: Excess Permit Holdings—Determinants

	(1)	(2)	(3)	(4)	(5)	(6)
Free Allocation	0.001***	0.001***	0.001***	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Log Emissions	-0.092***	-0.290***	-0.091***	-0.152***	-0.271***	-0.152***
	(0.007)	(0.030)	(0.007)	(0.011)	(0.047)	(0.010)
Emission Volatility	0.000*	0.000***	0.000	0.000**	0.000***	0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Total Emission Change	-0.034***	0.013	-0.035***	-0.032***	-0.023	-0.034***
	(0.007)	(0.018)	(0.007)	(0.008)	(0.032)	(0.009)
Current Emission Change	0.026*	0.002	0.014	0.057***	0.009	0.053***
	(0.015)	(0.013)	(0.013)	(0.021)	(0.017)	(0.020)
Total Assets				0.051***	-0.000	0.048***
				(0.014)	(0.025)	(0.016)
Liquidity				0.124	-0.062	0.148*
				(0.088)	(0.080)	(0.086)
Leverage				-0.222**	0.019	-0.216**
				(0.087)	(0.045)	(0.086)
Emission Intensity				-0.592	6.470***	-0.697
				(1.433)	(2.493)	(1.405)
Profitability				0.387***	0.065	0.340***
				(0.083)	(0.049)	(0.084)
Financial Constraints				0.911***	0.606***	1.017***
				(0.271)	(0.153)	(0.324)
Industry	Yes	No	No	Yes	No	No
Firm	No	Yes	No	No	Yes	No
Year x Industry	No	No	Yes	No	No	Yes
Observations	51,407	51,184	51,391	18,513	18,262	18,457
R2-Adjusted	0.32	0.71	0.35	0.38	0.84	0.39

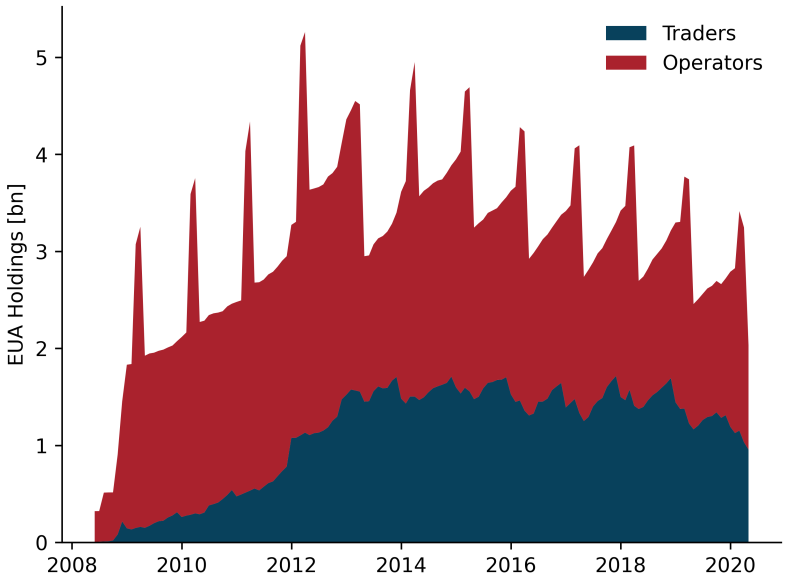
Note: Regression estimates as specified in Equation (3). The dependent variable *excess permit holdings* is the level of emission permit holdings at the end of each compliance cycle divided by the amount of permits surrendered in the same year. All variables are defined in Table A.1 and winsorized at the 1st and 99th percentiles. The sample period covers compliance cycles ending in 2009 through 2020. In parenthesis, I report standard errors clustered by *firm* and *compliance year x industry x country*. *p < .1; **p < .05; ***p < .01

Table A.7: Summary Statistics: Excess Permit Holdings and Price Uncertainty

Panel A:	Mean	P5	P50	P95	Std	Obs
Change in Holdings [%]	3.34	0.00	0.00	15.17	24.65	424,033
Carbon VIX Change [%]	-0.10	-12.23	-1.00	18.48	7.69	453,036
Carbon Price Return [%]	1.78	-28.92	2.31	19.93	13.50	453,036
Bid-Ask Spread [%]	21.38	8.76	22.04	35.33	8.95	453,036
Oil Price Return [%]	-1.90	-20.84	0.07	13.73	12.31	453,036
Market Price Return [%]	0.43	-5.67	1.06	6.20	3.92	453,036
Oil VIX Change [%]	1.04	-13.42	-0.43	15.29	16.38	453,036
Market VIX Change [%]	0.15	-6.98	-0.01	8.16	5.12	453,036
Panel B:	Mean	P2.5	P50	P97.5	Std	Obs
Change in Holdings [%]:						
Net Buyers	10.03	0.00	0	169.04	36.53	146,899
Net Sellers	-0.22	-6.84	0	5.67	13.65	277,134

Note: Summary statistics of monthly changes in carbon permit holdings and market characteristics of the panel outlined in Section III. Panel A includes the pooled data and Panel B divides changes in holdings by net sellers (net buyers) defined as firms with pre-trade excess holdings—including ex ante determined free allowances—of more (equal to or less) than 125% of their end-of-year emission obligations. The sample period is from 2013.09 to 2020.04. All variables are winsorized at the 1st and 99th percentile and defined in Table A.1.

Figure A.1: Aggregate Permit Holdings



Note: Aggregate monthly carbon permit holdings by firm type. Traders are financial firms owning trader accounts. Operators are firms owning at least one operating account linked to a regulated installation with positive emissions. The sample period is May 2008 to April 2020.

Table A.8: Robustness: Excess Permit Holdings and Price Uncertainty

	δH$_{t+1}$					
	Net Sellers = $\mathbb{1}_{\{EH_{i,t}>0\}}$		$\delta H_{t+1} <= 0$		Incl. Traders	
	(1)	(2)	(3)	(4)	(5)	(6)
Carbon VIX Changes	0.226***	0.195***	0.016***	0.016***	0.285***	0.292***
x Net Sellers	(0.042)	(0.042)	(0.005)	(0.006)	(0.050)	(0.051)
Carbon Price Return	0.156***	0.135***	0.007**	0.007**	0.186***	0.196***
x Net Sellers	(0.022)	(0.023)	(0.003)	(0.003)	(0.028)	(0.027)
Market Characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Transaction Cost	Yes	Yes	Yes	Yes	No	Yes
Firm Characteristics	No	Yes	No	Yes	No	No
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Net Sellers	Yes	Yes	Yes	Yes	Yes	Yes
Date x Industry	Yes	Yes	Yes	Yes	Yes	Yes
Date x Country	Yes	Yes	Yes	Yes	Yes	Yes
Observations	418,221	374,033	381,443	341,855	490,712	490,712
R2-Adjusted	0.14	0.13	0.08	0.09	0.15	0.15

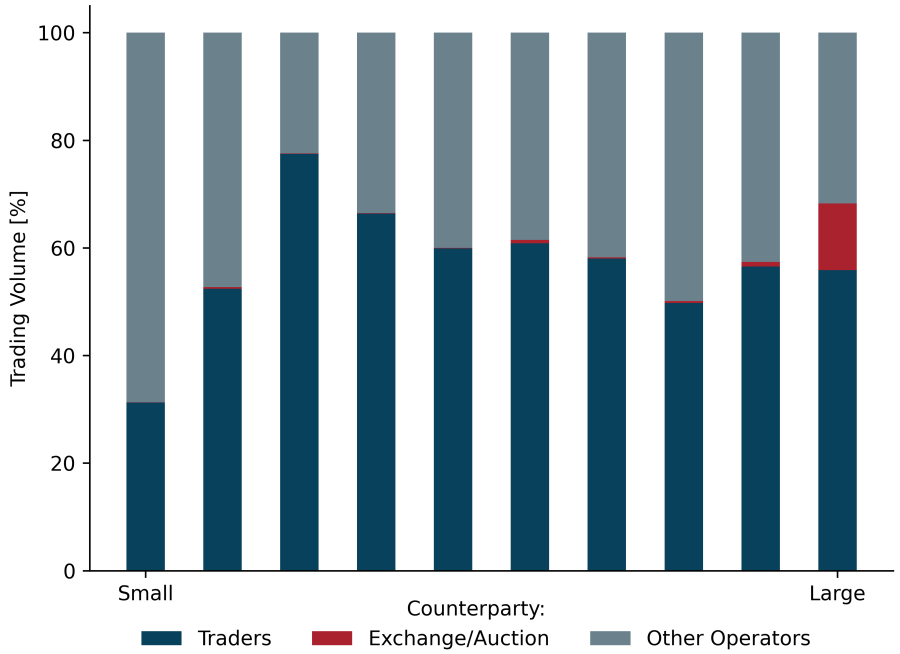
Note: Regression estimates of Equation (5). The dependent variable is one-month-ahead changes in emission permit holdings. The main independent variable is monthly changes in Carbon VIX interacted with an indicator of net sellers. Net sellers (net buyers) are firms with pre-trade holdings——including ex ante determined free allowances——of more (equal to or less) than 125% of their end-of-year emission obligations. The sample period is from 2013.09 to 2020.04. Columns (1) and (2) set the threshold for defining net sellers to 100%. Columns (2) and (3) subset the panel to non-positive changes in emission permit holdings. Columns (5) and (6) also include trades of financial firms. All variables are winsorized at the 1st and 99th percentile and defined in A.1. Standard errors are clustered at the *firm* and *month x industry x country* levels.

Table A.9: Summary Statistics: Excess Holdings and Future Carbon Emissions

	Obs	Mean	Std	P5	P50	P95
Future Emission Change	59,005	-0.01	0.32	-0.45	-0.02	0.35
Log Excess Holdings	59,106	0.81	0.61	0.00	0.74	1.91
Log Emissions	59,106	10.65	1.69	8.50	10.30	14.07
Emission Volatility [million]	46,762	3.94	12.55	0.00	0.42	19.90
Total Emission Change	55,477	0.12	1.10	-0.66	-0.06	1.40
Free Allocation Share [%]	59,106	118.10	135.16	8.54	97.49	264.55

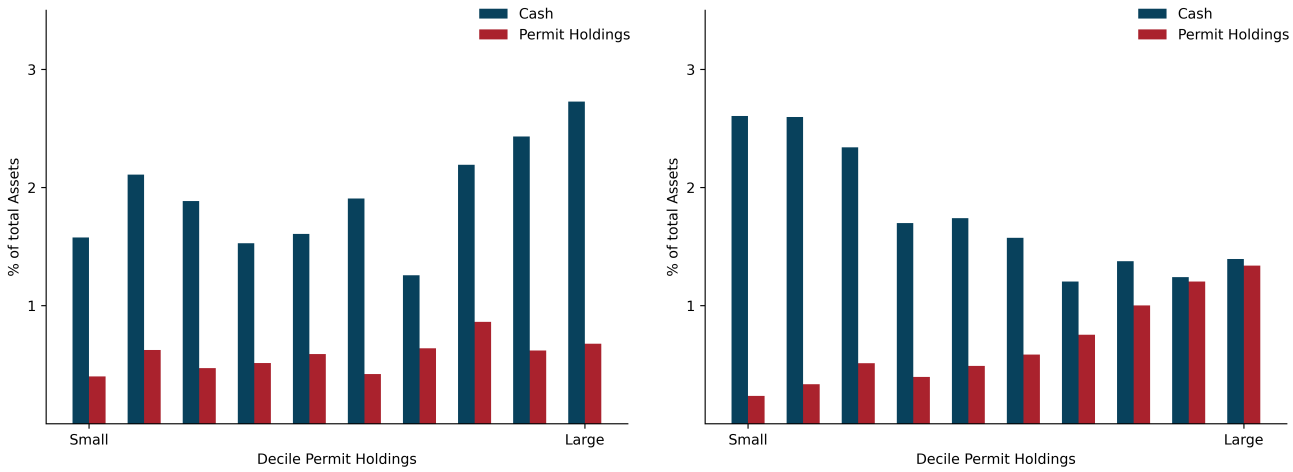
Note: Summary statistics of firms' annual excess permit holdings and carbon emissions. To avoid extreme outliers, I remove firm-year observations of the bottom emission quintile. All variables are winzorized at the 1st and 99th percentile and defined in Table A.1. The sample period overs compliance cycles ending in years 2009 to 2020.

Figure A.2: Source of Permit Holdings



Note: Share of operators' trading volume by counterparty. Trading volume is the total trading volume by operators. Each bar corresponds to a decile of permit holdings where *small* is D1 and *large* is D10, respectively. Exchange/Auction corresponds to transaction volumes with the auction account or secondary market accounts, such as that of the intercontinental exchange.

Figure A.3: Value of Permit Holdings



(a) Pre 2018

(b) Post 2018

Note: Annual average of median emission permit holdings as well as holdings of cash and cash equivalents as a fraction of firms' total assets by deciles of firms' emission permit holdings. The Euro value of firms' emission permits is recorded at the end of each compliance cycle at the end of April each year. Panel (a) shows the ratio of cash and emission permit holdings before up until the compliance cycle ending in April 2018 when permit prices were low. Panel (b) shows both measures from 2018, when carbon prices were high.