

Do carbon prices affect stock prices?

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Abstract

We explore how carbon pricing affects corporate financial performance during Phase 3 of the European Union Emissions Trading Scheme (EU ETS). We find that the relationship between carbon prices and stock prices depends critically on the proportion of verified emissions covered by freely allocated ETS allowances: For firms with a greater shortfall in emissions allowances (a greater permit coverage), an increase in daily carbon prices is associated with a decrease (increase) in contemporaneous stock prices. We provide additional evidence that firms with a significant permit shortfall reduce verified emissions in the EU, with no apparent carbon-leakage.

JEL CLASSIFICATION

G12, G30, Q54, Q58

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1 | INTRODUCTION

The European Union launched the EU Emissions Trading Scheme (EU ETS) in 2005 as its flagship policy to drive reductions in greenhouse gas (GHG) emissions and the transition to a net-zero carbon economy. The EU ETS is currently in Phase 4 (2021–2030). Phases 1 (2005–2007) and 2 (2008–2012) were largely institutional experimentation phases with respect to the allocation, trading, and banking of carbon emission allowances. During Phase 3 (2013–2020), the focus of our study, the EU ETS underwent significant changes and attained maturity. First, an EU-wide cap on verified emissions was introduced, which decreased annually by a linear reduction factor of 1.74%. Second, the proportion of emissions allowances that were allocated for free decreased significantly. For example, free allocations to manufacturing firms decreased from 80% in 2013 to 30% in 2020. Third, the expansion of sectors included in the ETS increased, with more firms subject to carbon pricing. Most importantly, the cost of emission allowances increased sixfold over Phase 3, rising from €5 for a ton of carbon dioxide (CO₂) in 2013 to €30 in 2020.

In this paper, we examine whether the EU cap-and-trade system during Phase 3 has had an effect on stock prices of the companies included in the EU ETS. We focus on Phase 3 (2013–2020), when the EU ETS entered a mature phase. During this period carbon prices became an economically significant cost for regulated firms. We construct firm-specific exposures to EU carbon prices, by linking installations in the EU ETS Union Registry to the parent company, specifically firms that are listed in stock exchanges in Europe. Through these ownership links, we obtain data on the total amount of allowances allocated for free (hereafter referred to as “free permits”) and the verified emissions for these firms. Our empirical results suggest that the relationship between carbon prices and stock prices depend critically on the amount of verified emissions covered by free permits: stock prices of firms with (without) sufficient free permits to cover verified emissions are positively (negatively) associated with carbon prices. We provide suggestive evidence that this pricing effect is driven by a profitability channel. We further analyze the real effects of carbon pricing, and find that while firms lower verified emissions in the EU, there is no effect on global emissions, investment, or innovation.

We frame our analysis with a simple static model with carbon pricing and financial constraints to examine the relationship between carbon prices and company valuation. The key feature of the model is that when there are financial constraints, an additional euro in internal funds is worth more than a euro. As a result, firm value is increasing in carbon prices if a firm has an allowance surplus, but decreasing in carbon prices if a firm has an allowance shortfall.

To empirically test these hypotheses, we construct a sample of firms regulated by the EU ETS that are listed on stock exchanges in the EU. We identify close to 3,000 installations that are owned by 366 listed companies in the EU (approximately 11,000 installations are owned by non-listed firms). We obtain daily stock returns data from Datastream, daily carbon prices data from the European Energy Exchange, annual corporate financial data from Orbis, and annual global carbon emissions data from Trucost. For these companies we can establish a direct link between carbon prices and their stock returns, operating performance, and emissions activities in the EU and globally.

We begin the empirical analyses by examining whether carbon prices are a random walk. Using the Augmented Dickey-Fuller test (Dickey & Fuller, 1979), we fail to reject the null hypothesis that carbon prices follow a unit root process in the models (1) without an intercept, (2) with a time trend, and (3) with drift. This means that the carbon price at day τ is the best predictor for the carbon price at day $\tau + 1$. In other words, daily carbon prices capture the unexpected component in the change of carbon prices.

We then proceed to examine the relationship between stock prices and carbon prices. We employ a fixed effects methodology that associates daily realized stock returns with daily changes in carbon prices and a carbon price exposure variable. We include day fixed effects to absorb time-varying unobserved heterogeneity at the daily level, and industry and country fixed effects to absorb time-invariant unobserved heterogeneity at the industry and country levels, respectively. Under this specification it is more plausible that carbon price changes and stock price changes on a daily frequency can be taken as exogenous price changes. Indeed, it is unlikely that endogenous

corporate decisions that could simultaneously affect both stock prices and carbon prices are taken on a daily frequency. It is highly likely that corporate operations do not change much from day to day, so that the daily innovations in both carbon price and stock price are not linked through some unobserved endogenous corporate decisions. We find that firms with more free permits benefit from higher carbon prices: For firms with the log of one plus free emissions one standard deviation above the mean, a 1% increase in daily carbon price is associated with 0.0036% higher realized stock returns. This result is consistent with findings in prior literature (e.g., Mo et al., 2012; Oberndorfer, 2009; Oestreich & Tsiakas, 2015; Zhu et al., 2018).

We further refine our measure of a firm's exposure to carbon prices by introducing an allowance shortfall variable. We define the following shortfall variable, which captures the percentage of verified emissions that are not covered by free permits. Firms with sufficient free permits to cover their verified emissions will have a shortfall ratio of 0, whereas firms without any permit will have a shortfall ratio of 1. Firms with a positive shortfall are required to purchase additional emission allowances, and are therefore negatively exposed to carbon prices. We interact this shortfall variable with emission levels and the change in carbon prices, and find that firm value is increasing for firms with more free permits than their verified emissions, but decreasing for firms with a significant permit shortfall. Based on our estimates, a 1% increase in carbon prices is associated with a 0.0134% higher stock price for firms without a permit shortfall. In contrast, a 1% increase in carbon prices is associated with a -0.061% lower stock price for firms with a complete shortfall (i.e., without any free permit).

Next, we examine whether these effects depend on the level of carbon prices. Carbon prices stayed below €10 from 2013 to 2017, but surged from 2018 to 2020, reaching €33 by the end of our sample period. In other words, the economic significance of carbon prices increased substantially in the later period. We find that the key coefficients are only significant in the 2018–2020 sub-period, indicating that the effects are indeed driven by the period when carbon prices became more material.

Based on these results, we explore whether a profitability (cash-flow) channel could explain these findings. With relevant earnings variables only available at annual frequency, we use firm-year level data for this analysis. We employ a similar fixed effects methodology, using the log of year-end carbon price, adjusted for fiscal year-ends, rather than changes in carbon prices. For emitting firms without any free permits, a 1% increase in year-end carbon price is associated with -0.0152 (-0.0376) lower return on assets (equity) relative to a firm with sufficient permits to cover its verified emissions. Relative to the mean return on assets (equity), this translates into a 26.6% (25.8%) lower profitability. These results suggest a profitability channel behind our stock price results, where the valuation effects reflect differences in corporate profitability due to carbon pricing and different allowance coverage across firms.

In light of these valuation effects, we also examine whether carbon pricing affects real outcomes. Specifically, we hypothesize that firms that are penalized by carbon pricing (i.e., firms with a significant shortfall), are firms with the most incentives to adjust emitting activities. First, we examine emission levels and find that firms with a significant permit shortfall have reduced their regulated emissions in the EU when carbon prices were higher. We do not find similar effects for non-EU scope 1 emissions. We also find that scope 2 emissions increase for these firms, suggesting that they partially switch their energy use to electricity, when carbon prices increase. We do not find that these firms invest more, although we find some positive effects on innovation. While these findings do not lend themselves to a causal interpretation, they hint to possible limitations of carbon pricing that is limited in scope. Together, these findings suggest that while the EU carbon price has reached levels in the later years of Phase 3 that materially penalize firms with a shortfall in free permits, the EU carbon price seems to only affect regulated carbon emissions.

There is a small literature that looks at the effects of the EU ETS on corporate valuations. Most existing studies on how carbon pricing affects company valuation and financial performance focus on Phase 1 (2005–2007), when an excess of emission allowances led to the eventual collapse of the carbon price, and on Phase 2 (2008–2012), when the successive financial and Euro crises and the resulting decrease in demand for allowances also depressed the carbon price. These studies use a variety of methodologies but do not use firm-specific exposure to carbon

prices in examining valuation effects.¹ Given the broader context around Phases 1 and 2, it is not surprising that the studies covering these phases have not found conclusive evidence of an effect of carbon pricing on profitability or stock returns. Bushnell et al. (2013), Oberndorfer (2009), Veith et al. (2009), and Zhu et al. (2018) interpret their results through a cost pass-through channel, with firms being able to pass on the increases in carbon prices to consumers. Mo et al. (2012), Oberndorfer (2009), Oestreich and Tsiakas (2015), and Zhu et al. (2018) also highlight the role of windfall gains from free allocations and the change in permit allocations between Phase 1 and Phase 2. Finally, Zhu et al. (2018) also find that carbon price changes are positively associated with stock returns during Phase 1, and negatively associated with stock returns in Phase 2. They suggest that this reversal may have been due to the global financial crisis and the European sovereign debt crisis. By constructing firm-specific exposures to carbon prices using ETS emissions data, we contribute to this literature by showing that the relationship between carbon prices and stock returns depends critically on permit coverage. We also provide evidence that the effects may be driven by a profitability channel, which is partially consistent with the windfall hypothesis but not the cost pass-through hypothesis.²

In independent work Millischer et al. (2023) (MEF) have undertaken a closely related study. While they address the same basic question and cover much of the same data, we choose and justify different empirical specifications that result in critically different interpretations and implications of the results. Given the closeness of their study we provide greater detail on the commonalities and key differences in approaches. The two studies cover similar sample periods and a similar sample of companies.^{3,4} The two studies, however, consider distinct—albeit similar on the surface—empirical specifications. MEF estimate the direct effect of carbon prices on stock prices, whereas we compare the differential effects of carbon pricing on stock prices and operations conditional on permit shortfall.⁵ This results in three sets of findings with markedly different financial and policy implications. First, by explicitly accounting for a firm's net exposure to carbon prices, we identify the negative effect of carbon prices for firms that have a permit shortfall, and the positive effect for firms that have a surplus of emission permits. This result, while intuitive, has not been documented in the prior literature. Second, we provide evidence for a profitability channel. This cash-flow based mechanism suggests that the ETS can indeed provide economy-wide cost incentives. Our findings imply that an ETS can be instrumental in facilitating the transition to a low-carbon economy. Third, we estimate the real effects of European Union Allowance (EUA) prices on verified and non-verified emissions, as well as investment and research and development, which reveal additional insights into the strengths and limitations of the cost incentives provided by carbon pricing.

Our paper is also related to a strand of literature that uses firm-level global carbon emissions to study the relationship between carbon emissions and stock returns. Bolton and Kacperczyk (2021) provide evidence that investors demand compensation for exposure to carbon emissions risk in the US, and Bolton and Kacperczyk (2023) provide evidence that carbon transition risk is priced globally in stocks and varies with investor awareness, the size of the renewable energy sector, and carbon emissions regulatory risk. Our study uses firm-level carbon emissions under the EU ETS to capture a firm's exposure to carbon pricing, and shows that carbon prices affect stock prices via a profitability channel.

Finally, our paper is related to the literature on the effectiveness of climate policies. An important question is whether emissions reductions achieved through carbon pricing are undone by firms switching activities to jurisdictions

¹The empirical methodologies fall into two large categories. First, Mo et al. (2012), Oberndorfer (2009), and Veith et al. (2009) perform security level analyses using multifactor models. Second, Oberndorfer (2009), Scholtens and van der Goot (2014), and Zhu et al. (2018) perform industry or sector level analyses using portfolios. Additionally, Zhu et al. (2018) use a quantile regression methodology to study whether carbon prices affect markets with higher and lower returns differently. Bushnell et al. (2013) use an event study methodology to study how stock prices respond to large swings in carbon prices.

²If the cost pass-through hypothesis holds, we should find revenue to be positively associated with carbon prices. However, in results available upon request, we find that the log of sales is not significantly related to the log of carbon prices.

³Our sample period begins in 2013 and ends in 2020, covering the entire Phase 3 of EU ETS. MEF include the first year of Phase 4.

⁴They take comparable approaches to matching installations under the EU ETS with their listed parent companies. Our matching procedure builds on Martin et al. (2014) whereas MEF rely on a procedure developed by Jaraitė et al. (2014). MEF match 5,800 account holders in the EU ETS with companies in Orbis and identify 2,112 account holders that are controlled by 338 listed companies. We identify 13,143 installations (nearly the entire universe of the EU ETS in Phase 3). Of these, we identify 3,221 installations that are owned by 366 listed companies.

⁵Furthermore, MEF consider changes on a weekly frequency, whereas we look at daily changes. They include industry-month fixed effects, whereas we include day (and industry) fixed effects, which absorb the direct effect of carbon prices on stock prices. MEF cluster standard errors by firms, whereas we cluster by firm and date.

where they can escape carbon pricing. We find that there is no carbon leakage in Phase 3 for the regulated firms in our sample. Indeed, EU carbon prices have had no significant effect on firm-level non-EU scope 1 emissions. Most closely related to this paper is Dechezleprêtre et al. (2022), who show that in between 2007 and 2014, modest carbon prices did not induce multinational companies to displace their carbon emissions from Europe to non-EU subsidiaries. The wider literature is surveyed in Martin et al. (2016). Also, using administrative data on French manufacturing firms, Colmer et al. (2025) find that regulated firms reduce carbon emissions by 14%-16% and increase targeted investments, without an increase in imports in Phase 2. Focusing on foreign direct investment, Borghesi et al. (2020) provide some evidence of the establishment of foreign subsidiaries and a larger effect on production in existing foreign subsidiaries among Italian firms, and Koch and Basse Mama (2019) find a small effect in German multinational firms that are less capital intensive. Using the Californian cap-and-trade program, Bartram et al. (2022) show that financially constrained firms shift production and emissions out of California. Focusing on the syndicated loan market, Benincasa et al. (2022) find that increases in domestic climate policy stringency leads to an increase in cross-border lending, which suggests possible carbon leakage via debt markets. Our paper shows that while higher carbon prices in the EU ETS lowers emissions within the EU for firms with a significant permit shortfall, global emissions for these firms remain unaffected. This suggests that a regional cap-and-trade system only has regional effects.

2 | INSTITUTIONAL BACKGROUND

The EU ETS, set up in 2005, is the first international cap-and-trade scheme on greenhouse gas emissions.⁶ Under the system, emissions from operating installations must be covered by tradeable emissions allowances. Each allowance gives the holder the right to emit one ton of CO₂, or the equivalent amount of other powerful greenhouse gases (European Commission, 2022d). The purpose of the trading of allowances is so that “emissions are cut where it costs least to do so”, and to promote investment and innovation in low-carbon technologies (European Commission, 2022c).

There have been several phases in the development of the EU ETS. Phase 1 (2005–2007) and Phase 2 (2008–2012) were largely institutional experimentation phases, which involved setting up the infrastructure and coverage of the trading scheme. Significant changes have been made during Phase 3 (2013–2020), the sample period of this study. First, an overall EU cap on allowable emissions was introduced, which decreases by a linear reduction factor of 1.74% annually (European Commission, 2022d). Second, the main method for the distribution of allowances was via auction rather than free allowance grants: 57% of allowances were auctioned off (European Commission, 2022e) and free allocations for manufacturing firms decreased from 80% in 2013 to 30% in 2020 (European Commission, 2022a). Electricity producers were required to purchase all their allowances, although some free allocations were permitted in EU member states that were modernizing their energy sectors (European Commission, 2022f).

During Phases 1 and 2 too many allowances had been granted, so that the carbon price plunged to €0.10 in Phase 1, and €2.81 in Phase 2. It was only in late Phase 3 that the allowance price reached levels that analysts deemed material. Carbon prices have languished substantially below €10 per ton of CO₂ from 2013 – the beginning of Phase 3 – to 2018. However, carbon prices rose significantly in 2018, from a low of €7.62 on January 8, 2018 to a high of €33.28 on December 28, 2020. In the spring of 2022 the carbon price briefly exceeded €90 per ton of CO₂.⁷ Given that emissions allowance prices were so low for so long it is reasonable to expect that the impact of carbon pricing on financial performance and stock valuations only manifested themselves in the following years, when the carbon price began to rise above €20.

⁶The EU ETS covers (1) CO₂ from electricity and heat generation, and production activities in energy-intensive industry sectors, (2) nitrous oxide (N₂O) from production of nitric, adipic, and glyoxylic acids, and glyoxal, and (3) perfluorocarbons (PFCs) from the production of aluminium (European Commission, 2022c).

⁷Reuters reported that analysts on average expected carbon prices to be €84.14 in 2022, €91.71 in 2023, and €94.11 in 2024. See <https://www.reuters.com/business/energy/analysts-raise-eu-carbon-price-forecasts-gas-rally-persists-2022-01-25/>.

3 | PREDICTIONS FROM A SIMPLE MODEL WITH FINANCIAL CONSTRAINTS

We consider a single firm in a simple static setting where the firm can invest in carbon emission abatement and/or asset maintenance at the end of a first production and sales cycle.⁸ These investments, in turn, generate a continuation value V . The firm has an operating asset K . The operating asset generates cash-flow $Y = AK$ and carbon emissions $C = \lambda K$. The firm has a carbon emission allowance E . If $E < \lambda K$ the firm must purchase additional allowances at price p , and if $E > \lambda K$ the firm can generate additional cash-flow $p(E - \lambda K)$.

End of period cash-flows are therefore equal to

$$Y + p(E - \lambda K), \quad (1)$$

and the firm's accumulated internal funds at the end of the period are

$$w = Y + p(E - \lambda K). \quad (2)$$

At the end of the period the firm can make capital expenditures I to either reduce its emissions from operations going forward or maintain its operating asset. The investment has decreasing returns: By investing I the firm generates an incremental cash flow $f(I) > 0$ going forward which is increasing and concave in I : $f'(I) > 0$ and $f''(I) < 0$.

The firm's internal funds w may not be sufficient to fund its desired capital expenditures. The firm can raise additional external funds, but these are more costly (that is a simple way of modelling financial constraints). If the firm raises outside funds o it incurs a cost $\psi(o)$. We assume that $\psi(o)$ is increasing and convex: $\psi_o > 0$ and $\psi_{oo} \geq 0$. The firm chooses its investment level I and outside financing o to maximize its payoff:

$$\max_{I,o} f(I) + w - [I + \psi(o)], \quad (3)$$

where $o = \max\{I - w, 0\}$. We denote by $V(w)$ the firm's continuation value as a function of its internally accumulated funds w .

When the firm has sufficient internal funds, or when there are no additional costs from outside funds the first-best optimal investment level is given by the first-order condition:

$$f'(I^{FB}) = 1. \quad (4)$$

The firm is financially constrained if $w < I^{FB}$ and if $\psi(o) > 0$ for any strictly positive amount of outside funds o . In that case the firm uses up its internal funds w first and raises the additional amount of funds $o = \max\{I - w, 0\}$ from outside capital markets. The firm's optimal investment level I^* is then given by the following first-order condition:

$$f'(I^*) = 1 + \psi_o(I^*(w) - w). \quad (5)$$

The value of the firm after substituting for $I^*(w)$ (given by (5)) into its payoff function (3) is then given by:

$$V^*(w) = f(I^*(w)) + w - [I^*(w) + \psi(o^*(w))], \quad (6)$$

⁸Hepburn et al. (2013) analyze a more general oligopolistic industry equilibrium model with verified emissions subject to an ETS. They show that carbon pricing in a Cournot oligopoly does have a financial impact if freely allocated permits cover a fraction of emissions that is smaller than the industry Herfindahl index.

where $o^*(w)$ is the outside financing amount

$$o^*(w) = I^*(w) - w. \quad (7)$$

From the envelope theorem, we then obtain the following key prediction:

$$V_w^*(w) = f'(I^*(w)) = 1 + \psi_o(e^*(w)) > 1. \quad (8)$$

In other words an additional dollar in internal funds is worth more than a dollar. This is a robust prediction that continues to hold in dynamic settings as shown in Bolton et al. (2011).

Consider finally the effects of a change in EUA price p on firm value. We have

$$\frac{dw}{dp} = (E - \lambda K).$$

Therefore,

$$\frac{\partial V^*(w)}{\partial p} = f'(I^*(w))(E - \lambda K),$$

so that firm value (or the stock price) increases with the EUA price p when the firm has an allowance surplus $E > \lambda K$, and decreases with the EUA price p when it has an allowance shortfall $E < \lambda K$. Moreover, the size of the effect of a change in EUA price is bigger the larger the allowance surplus or shortfall.

For simplicity we have illustrated the main relevant prediction for our analysis — that firm value increases with the EUA price p when the firm has an allowance surplus — in a static setting. The model can be extended to a dynamic setup as in Bolton et al. (2011), and it can be shown that the key prediction extends to such a dynamic setting. The additional consideration that can be introduced in the dynamic model is the choice for the firm to sell or bank any surplus in allowances at any moment in time. The firm will then prefer to sell rather than hoard its surplus allowances if the EUA price p exceeds the shadow value of its allowances. Either way, simple revealed preference logic implies that a firm with a surplus of allowances will always benefit from an increase in the EUA price p (and a firm with a shortfall will always be made worse off).

4 | EMPIRICAL SETTING

This section describes the data sources, variables and empirical specification.

4.1 | Data

4.1.1 | ETS carbon emissions data

We have obtained EU ETS emissions trading data from the European Union Transaction Log (EUTL). The EUTL is a registry run by the European Commission, which records and verifies all transactions in the trading system, and is publicly available. It provides verified carbon emission levels for each regulated installation on an annual basis. We refer to these emissions as “regulated emissions”. The EUTL also reports the number of allowances that are allocated for free to each installation every year. Specifically, the EUTL provides a breakdown of: (1) allowances allocated free of charge to existing installations; (2) allowances allocated free of

charge for the modernization of electricity generation; and (3) allowances allocated free of charge from the new entrant reserve.⁹

We match the EUTL data for ETS installations with the Orbis data from Bureau van Dijk that provides financial data on corporations. Our matching procedure involves two steps. In the first step, we match ETS installations to firms in Orbis using national identifiers. In the second step, we match the installations with no national identifiers to firms via a name-matching algorithm and verify the matches based on country and sector information. The match between the installations in the EUTL and the firms in Orbis allows us to identify the listed parent companies by utilizing Orbis' ownership information on immediate shareholders, domestic ultimate owners, and global ultimate owners.¹⁰ We then construct firm level ETS emissions and free allocations by aggregating across installations owned by the same publicly listed corporation each year.

In Phase 3 of the EU ETS (2013–2020), there were 13,914 stationary ETS installations in the EUTL. For 13,143 of these, corresponding to 97% of ETS emissions, we established matches to Orbis firms. Given that many firms run more than one ETS installation, our final list comprises 7,985 Orbis firms. Using ownership information from Orbis, we determined that close to 10,000 installations are part of (ultimately) privately owned companies, whereas 3,221 installations were identified as being owned by 366 publicly traded companies. We further require firms (1) to be listed in a country covered by the EU ETS and (2) to have non-missing daily stock returns data. The final sample consists of 338 unique firms. Table B1 tabulates the filtering process. These represent close to 50% of EU ETS emissions, as reported in Table B2. There was a slight increase in the number of firms during Phase 3. These firms are primarily manufacturing firms from the United Kingdom, Germany and France. Table 1 provides descriptive statistics of the sample.

4.1.2 | Trucost global emissions data

We also match the Trucost data on firm-level carbon emissions to our sample of 338 firms. The Trucost EDX dataset reports carbon emissions resulting from firms' economic activity as described in detail in Bolton and Kacperczyk (2021). These are divided into three categories: (1) Scope 1 emissions that result directly from production; (2) Scope 2 indirect emissions that arise from the production of the electricity (or heat or steam) the firm has bought and consumed; and (3) Scope 3 upstream indirect emissions that occur through the supply chain, waste disposal, or outsourced activities. Our primary focus is on Scope 1 emissions.

4.1.3 | EU allowance price data

We obtain daily spot prices for emissions allowances from the European Energy Exchange (EEX). EEX offers spot and derivative products on EU allowances and has been an auction platform for the EUAs during Phase 3.

Figure 1 plots the daily spot settlement price for EU allowances. Between 2013 and 2018, the daily spot price fluctuated between €5 and €10. The strong upward trend from 2018 onward is, according to experts, due to a combination of three factors (European Central Bank, 2021). First, the aggregate emission allowances (the EU-wide cap in emissions) have been gradually reduced by 1.74% every year. Second, reforms in the allocation of allowances have been introduced, which further affected the carbon price. Mainly, the share of auctioned allowances has increased, and a market price stabilization mechanism, the Market Stability Reserve (MSR), has been introduced, which can hold an inventory of allowances so as to smooth year-by-year variations in the supply of excess

⁹The New Entrants Reserve (NER) is a reserve of emission allowances for new installations (and existing installations that increase capacity and are eligible for additional free allocations).

¹⁰Ownership linkages in Orbis Europe are "current" and do not keep track of past changes in ownership. We use ownership linkages as of December 2020.

TABLE 1 Sample description.

<i>Panel A: Year</i>	
Year	ETS Firms
2013	311
2014	314
2015	320
2016	323
2017	326
2018	327
2019	323
2020	315
<i>Panel B: Country</i>	
Country	ETS Firms
Austria	10
Belgium	13
Croatia	1
Cyprus	1
Czech Republic	2
Denmark	4
Estonia	1
Finland	14
France	43
Germany	45
Greece	4
Hungary	3
Ireland	10
Italy	23
Luxembourg	5
Netherlands	16
Norway	9
Poland	20
Portugal	6
Romania	1
Slovenia	1
Spain	27
Sweden	18
United Kingdom	61
Total Unique Observations	338

Panel C: Industry	
NACE Main Section	ETS Firms
Mining And Quarrying	23
Manufacturing	181
Electricity, Gas, Steam And Air Conditioning Supply	38
Water Supply; Sewerage, Waste Management And Remediation Activities	6
Construction	16
Wholesale And Retail Trade; Repair Of Motor Vehicles And Motorcycles	9
Transportation And Storage	15
Information And Communication	10
Financial And Insurance Activities	18
Real Estate Activities	1
Professional, Scientific And Technical Activities	12
Administrative And Support Service Activities	7
Public Administration And Defence; Compulsory Social Security	1
Other Service Activities	1
Total Unique Observations	338

Notes: This table tabulates descriptive statistics of the sample. Panel A tabulates the number of unique firms by year. Panel B tabulates the number of unique firms by headquarters country. Panel C tabulates the number of unique firms by industry using the Statistical Classification of Economic Activities in the European Community (NACE).

allowances. Third, expectations of tighter future climate policies have shifted, with investors expecting a more rapid phase-out of free allowance allocations. Indeed, the EU Commission published the revised EU ETS Directive for Phase 4 in April 2018, and announced the European Green Deal at the end of 2019. Both of these announcements increased the credibility of the EU ETS scheme and hence carbon prices. (European Central Bank, 2021).

4.1.4 | Stock prices, financial, and global emissions data

We obtain daily stock prices in Euros from Datastream. As highlighted previously, firm financial data is obtained from Orbis.

4.2 | Variable construction

This section defines and describes our main variables. Summary statistics are reported in Table 2.

4.2.1 | Emissions variables

We construct the variable $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$, the log of one plus firm i 's freely allocated ETS emission allowances in year $t - 1$, to measure the size of a firm's exposure to EUA prices. Free permits have been included in

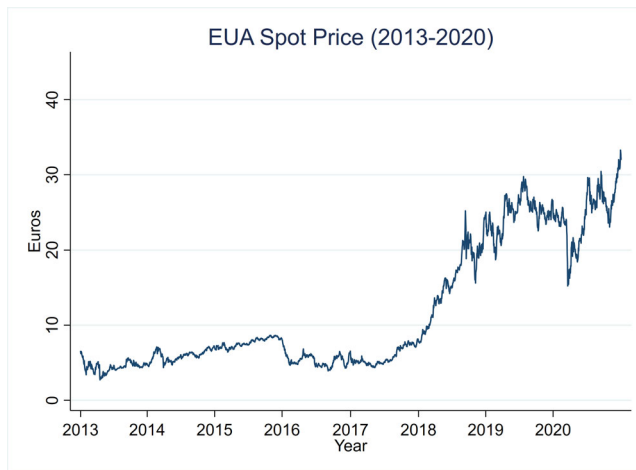


FIGURE 1 EUA spot settlement prices (2013–2020). This figure plots the time series of daily EUA spot settlement prices in euros during the EU Emissions Trading System Phase 3 (2013–2020). [Color figure can be viewed at wileyonlinelibrary.com]

the design of the ETS to forestall carbon leakage (European Commission, 2022b). At the beginning of Phase 3, manufacturing firms on average received 80% of their emission allowances for free. This fraction gradually decreased to 30% by 2020 (European Commission, 2022e). As a large proportion of emission allowances were freely allocated, the correlation coefficient between firm-year level freely allocated allowances and firm-year level verified emissions was high, standing at 0.71 over Phase 3. As some emitting firms receive a large amount of free permits while others do not, we add 1 to a firm's $FREE\ EMISSIONS_{it-1}$ before log-linearizing it. The sample mean is 10.4720, with a standard deviation of 4.5921. To aid interpretation, we standardize $LOG(1 + FREE\ EMISSIONS_{it-1})$, by subtracting the sample mean and dividing by the sample standard deviation.

We then construct the variable $SHORTFALL\ RATIO_{it-1}$ to measure whether a firm is positively or negatively exposed to EUA prices. $SHORTFALL\ RATIO_{it-1}$ is the proportion of firm i 's verified ETS emissions not covered by freely allocated ETS allowances in year $t - 1$.¹¹ A firm with a $SHORTFALL\ RATIO_{it-1}$ of 0 has sufficient free permits to cover its verified emissions in year $t - 1$, whereas a firm with a $SHORTFALL\ RATIO_{it-1}$ of 1 has no free permit to cover any of its verified emissions. A higher $SHORTFALL\ RATIO_{it-1}$ implies that a firm is required to purchase more emission allowances (as a proportion of verified emissions) either in the auction or in secondary markets to cover the shortfall. The sample mean of $SHORTFALL\ RATIO_{it-1}$ is 0.3222, with a standard deviation of 0.3390.¹² As shown in Figure 2, the proportion of firms with a shortfall ratio greater than 0.5 has increased over Phase 3, suggesting that there was an increasing proportion of firms with a significantly negative exposure to carbon prices.¹³

¹¹ $SHORTFALL\ RATIO_{it-1}$ is defined as follows: $SHORTFALL\ RATIO_{it-1} = 1 - \min\left(\frac{FREE\ EMISSIONS_{it-1}}{VERIFIED\ EMISSIONS_{it-1}}, 1\right)$.

¹²Table B3 in the Internet Appendix reports summary statistics on the value of permit shortfall. The mean of permit shortfall in our sample is €26.078M, but the median value is €692,700, implying that the distribution of the value of shortfall is skewed and contains outliers. To put these numbers into perspective, we scale $SHORTFALL\ VALUE_{it}$ by total assets to capture the differences in firm size, and by the cost of goods sold to capture how important permit shortfall is relative to total firm-level input costs. The mean for $SHORTFALL\ VALUE_{it}/ASSETS_{it-1}$ ($SHORTFALL\ VALUE_{it}/COGS_{it-1}$) is at 0.18% (0.64%), the maximum value is 11.32% (24.2%), suggesting significant heterogeneity at the right tail.

¹³In Table B4 of the Internet Appendix, we provide additional summary statistics to show that our measure captures a firm's exposure to carbon prices that cannot be fully reflected in emission intensity. Panel A shows that while $SHORTFALL\ RATIO_{it-1}$ is significantly positively correlated with $EMISSION\ INTENSITY_{it-1}$, the magnitude is low (0.059). As $EMISSION\ INTENSITY_{it-1}$ exhibits significant skewness, we log-linearize $EMISSION\ INTENSITY_{it-1}$ and find that the correlation coefficient with $SHORTFALL\ RATIO_{it-1}$ is 0.457. In Panel B, we provide additional summary statistics to show that despite sector-specific allocation rules, $SHORTFALL\ RATIO_{it-1}$ exhibits significant heterogeneity within an industry.

TABLE 2 Summary statistics.

Variable	Mean	SD	25th Pct	50th Pct	75th Pct	Obs
<i>Panel A: Firm-Day Level Variables</i>						
RET_{it}	0.0311	1.9035	-0.9346	0.0000	0.9742	637311
$\text{LOG}(M/Bit - 1)$	-6.5000	0.7384	-6.9780	-6.4894	-6.0126	625910
$\text{LOG}(MV_{it-1})$	8.2552	1.7271	7.0082	8.3122	9.5521	637311
β_{it}^{SMB}	-0.2039	0.7067	-0.6862	-0.2156	0.2438	637311
β_{it}^{HML}	0.0374	0.9200	-0.5358	0.0103	0.5891	637311
β_{it}^{RMW}	0.0107	1.0539	-0.6039	0.0193	0.6387	637311
β_{it}^{CMA}	-0.0403	0.9677	-0.6190	-0.0355	0.5013	637311
β_{it}^{MKT}	0.6868	0.3506	0.4571	0.6622	0.8987	637311
β_{it}^{WML}	-0.0037	0.5900	-0.3216	0.0172	0.3466	637311
$VOLATILITY_{it}$	0.0194	0.0079	0.0141	0.0175	0.0225	637311
<i>Panel B: Firm-Year Level Variables</i>						
$CAPX_{it}/ASSETS_{it-1}$	0.0355	0.2363	-0.0214	0.0106	0.0498	2070
$CASH_{it-1}/ASSETS_{it-1}$	0.0892	0.0693	0.0413	0.0734	0.1181	2445
$INTENSITY_{it-1}$	0.4958	1.7171	0.0037	0.0444	0.2941	2265
$INTENSITY_{it-1}^{STANDARDIZED}$	-0.0729	0.0438	-0.0854	-0.0844	-0.0780	2265
$LEVERAGE_{it-1}$	0.0476	0.0550	0.0117	0.0319	0.0605	2441
$\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})^{STANDARDIZED}$	0.0513	0.9423	-0.1887	0.2393	0.6813	2265
$\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$	10.4720	4.5921	9.3028	11.3880	13.5420	2265
$\text{LOG}(ASSETS_{it-1})$	8.9389	1.8321	7.6727	8.8806	10.1970	2549
$\text{LOG}(EUA_{it})$	2.2140	0.6444	1.6771	1.8714	2.7613	2469
$\text{LOG}(\text{FREE EMISSIONS}_{it-1})$	11.8360	2.7568	9.9884	11.8200	13.8050	2006
$\text{LOG}(\text{FREE EMISSIONS}_{it-1})^{STANDARDIZED}$	-0.0200	0.9871	-0.6816	-0.0258	0.6849	2006
$\text{LOG}(INTENSITY_{it-1})$	-3.2025	2.8425	-4.9994	-2.7079	-1.1106	2101
$\text{LOG}(INTENSITY_{it-1})^{STANDARDIZED}$	-0.0048	0.9657	-0.6153	0.1632	0.7059	2101
$\text{LOG}(\text{NET SCOPE } 1_{it})$	13.3540	2.1445	11.8690	13.1370	14.9170	1622
$\text{LOG}(\text{SCOPE } 2_{it})$	12.5140	1.8201	11.3890	12.5960	13.7500	1622
$\text{LOG}(\text{VERIFIED EMISSIONS}_{it})$	12.2050	2.8290	10.1280	12.2670	14.3330	1622
$\text{LOG}(\text{VERIFIED EMISSIONS}_{it-1})$	12.1920	2.8452	10.0540	12.2450	14.3400	2101
$\text{LOG}(\text{VERIFIED EMISSIONS}_{it-1})^{STANDARDIZED}$	0.0318	0.9758	-0.7015	0.0498	0.7685	2101
$\text{LOG}(\text{TURNOVER}_{it-1})$	8.3577	1.6513	7.1943	8.3710	9.6146	2425
$\text{NET INCOME}_{it}/ASSETS_{it-1}$	0.0369	0.0566	0.0115	0.0354	0.0624	2070
$\text{NET INCOME}_{it-1}/EQUITY_{it-2}$	0.0932	0.2065	0.0393	0.0983	0.1619	2533
$R\&D_{it}/ASSETS_{it-1}$	0.0114	0.0230	0.0000	0.0011	0.0127	2070
SHORTFALL RATIO	0.3222	0.3390	0.0000	0.2242	0.5531	2260

TABLE 2 (Continued)

Variable	Mean	SD	25th Pct	50th Pct	75th Pct	Obs
TANGIBILITY _{it-1}	0.3506	0.2073	0.1870	0.3344	0.4917	2447
VERIFIED EMISSIONS _{it-1} /SCOPE 1 _{it-1}	0.3017	0.3055	0.0368	0.2051	0.5015	2068
<i>Panel C: Time Series Variables</i>						
ΔEUA% _τ	0.1440	2.9788	-1.4610	0.0000	1.7570	2029

Notes: This table tabulates summary statistics for the security-day sample. The sample period is 2013 to 2020. Variables are winsorized at the 1st and 99th percentiles. Data sources and variable definitions are in Table A1.

4.2.2 | Financial characteristics

We include a number of firm-level financial control variables that are likely to influence stock valuations. These comprise $CASH_{it-1}/ASSETS_{it-1}$, $LEVERAGE_{it-1}$, $LOG(ASSETS_{it-1})$, $LOG(MV_{it-1})$, where MV is given by the market capitalization of the company, $LOG(M/B_{it-1})$, where M/B is the market-to-book ratio, $LOG(TURNOVER_{it-1})$, $NET\ INCOME_{it-1}/EQUITY_{it-2}$, and $TANGIBILITY_{it-1}$.

4.2.3 | Security characteristics

We also compute factor loadings on the Fama-French 5-factor model (market risk, size, value, investment, and profitability) (Fama & French, 2015) and momentum using a 252-day rolling window, to control for stock price changes that may be driven by these factors. Finally, we compute stock price volatility using a 252-day rolling window.

4.3 | Empirical specification

4.3.1 | Firm-day level analyses

Our main empirical specification associates daily stock price changes with daily changes in carbon prices, taking into account a company's net exposure to EUA prices. We fully interact a firm's freely allocated allowances, shortfall ratio and the change in carbon prices, whilst controlling for company characteristics and other market risk factors that may affect the company's stock price:

$$\begin{aligned}
 RET_{it} = & \beta_1 LOG(1 + FREE\ EMISSIONS_{it-1}) \times SHORTFALL\ RATIO_{it-1} \times \Delta EUA\%_{\tau} \\
 & + \beta_2 LOG(1 + FREE\ EMISSIONS_{it-1}) \times \Delta EUA\%_{\tau} \\
 & + \beta_3 SHORTFALL\ RATIO_{it-1} \times \Delta EUA\%_{\tau} \\
 & + \beta_4 LOG(1 + FREE\ EMISSIONS_{it-1}) \times SHORTFALL\ RATIO_{it-1} \\
 & + \beta_5 LOG(1 + FREE\ EMISSIONS_{it-1}) + \beta_6 SHORTFALL\ RATIO_{it-1} \\
 & + \beta_7 \Delta EUA\%_{\tau} + \gamma^T x_{it-1} + \alpha_{\tau} + \epsilon_{it}
 \end{aligned} \tag{9}$$

where: RET_{it} is the percentage change of firm i 's stock price on day τ , $LOG(1 + FREE\ EMISSIONS_{it-1})$ is the log of one plus firm i 's freely allocated ETS emission allowances in year $t - 1$, $SHORTFALL\ RATIO_{it-1}$ is the proportion of firm i 's verified ETS emissions not covered by freely allocated ETS allowances in year $t - 1$, $\Delta EUA\%_{\tau}$ is the daily percentage

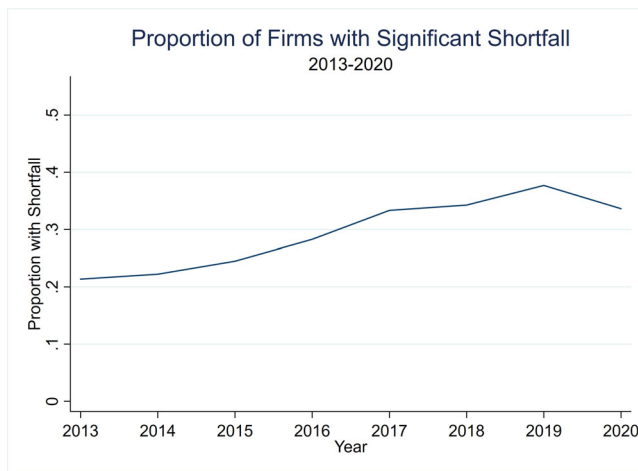


FIGURE 2 Proportion of firms with a significant permit shortfall (2013–2020). This figure plots the proportion of firms with a significant permit shortfall (i.e., proportion of freely allocated permits is less than 50% of verified emissions) in Phase 3 (2013–2020). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1111/jfr.12472)]

change in carbon prices from day $\tau - 1$ to day τ . We believe this empirical specification to be the best approximation of the information set of investors, as installation-level data on free permits and verified emissions is publicly available and updated annually.¹⁴ As β_1 is identified by the variation at the firm and date levels, we two-way cluster our standard errors at both levels.

The first set of control variables includes the following lagged annual firm-specific variables: $\text{LOG}(\text{ASSETS}_{it-1})$ in year $t - 1$, LEVERAGE_{it-1} the ratio of total debt to assets in year $t - 1$, $\text{TANGIBILITY}_{it-1}$ the ratio of PPE to total assets in year $t - 1$, $\text{NET INCOME}_{it-1}/\text{EQUITY}_{it-2}$ in year $t - 1$, $\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$ in year $t - 1$, and $\text{LOG}(\text{TURNOVER}_{it-1})$ in year $t - 1$. The second set of control variables include the following daily firm-specific variables: $\text{LOG}(M/B_{it-1})$ the market-to-book ratio on day $\tau - 1$, $\text{LOG}(MV_{it-1})$ on day $\tau - 1$, VOLATILITY_{it-1} the daily stock price volatility estimated using a 252-day rolling window, loadings on risk factors, market MKT , size SMB , value HML , operating profitability RMW , investment CMA , and momentum WML , calculated using a 252-day rolling window. We also include country, industry, and date (i.e., day) fixed effects. These control variables and fixed effects pick up other common sources of risk (than the risk with respect to changes in carbon allowance prices) that are tied to the company's operations and exposures to common aggregate risk factors. Importantly, the inclusion of the date fixed effects controls for any confounding effects at the date level, such as macroeconomic conditions and regulatory events. As $\Delta\text{EUA}\%_\tau$ only varies at the date level, the coefficient β_7 is absorbed and not estimated. This implies that our coefficient of interest, β_1 , only captures the joint variation between daily movements in carbon prices and firm-year emission variables.

We center our analysis around this main specification. An increase in carbon prices hurts the bottom line of firms, the impact of which is larger for firms with a greater amount of emissions not covered by freely allocated permits. To the extent that carbon prices have become a material cost during Phase 3, we expect β_1 to be significantly negative.

¹⁴While trading activity of emission allowances will influence a firm's real-time exposure to carbon prices, the effect of allowance trading will likely be secondary to the shortfall based on the difference between free allocations and verified emissions. Unlike data on verified emissions and free permits, there is a 3-year lag in the release of transaction level data. The significant costs associated with aggregating trading activity and the data release lags would mean that a real-time exposure is unlikely to be available to investors.

4.3.2 | Firm-year level analyses

As data on emissions and operations are only available at an annual frequency, we use the following empirical model at the firm-year level:

$$y_{it} = \beta_1 \text{SHORTFALL RATIO}_{it-1} \times \text{LOG}(EUA_{it}) + \beta_2 \text{SHORTFALL RATIO}_{it-1} + \beta_3 \text{LOG}(EUA_{it}) + \gamma^T x_{it-1} + \alpha_i + \alpha_t + \varepsilon_{it} \quad (10)$$

where: y_{it} is an outcome variable for firm i in year t . $\text{SHORTFALL RATIO}_{it-1}$ is the proportion of firm i 's verified ETS emissions not covered by freely allocated ETS allowances in year $t - 1$. $\text{LOG}(EUA_{it})$ is the log of carbon prices at fiscal closing date for firm i and year t . Since firms have different fiscal year end dates, $\text{LOG}(EUA_{it})$ is firm-year specific. For the firm-year level analyses, we use the level of carbon prices rather than percentage changes, given that annualized changes are less easy to interpret. Since we are regressing levels on levels, we include firm fixed effects (α_i) to absorb time-invariant unobserved heterogeneity.

5 | RESULTS

We begin by reporting our findings on carbon price dynamics. We then proceed to the analysis of the effect of changes in carbon prices on stock prices. We further explore the effects of changes in carbon prices on operating performance.

5.1 | Do carbon prices follow a random walk?

Are changes in carbon prices transitory or permanent shocks? This is a fundamental first question for our analysis, since transitory shocks are less likely to have an impact on stock prices. We perform augmented Dickey-Fuller tests to examine whether the daily carbon price follows a random walk (Dickey & Fuller, 1979); that is, whether carbon prices reflect all available information such that the change in carbon prices is a permanent shock. Since it is unclear a priori whether there is a time trend or a drift term in the evolution of carbon prices, we perform three versions of the test: (1) without an intercept, (2) with a linear time trend, and (3) with a drift term. We present our results (with the inclusion of one lagged difference and 30 lagged differences) in Table 3.

TABLE 3 EUA prices: Augmented Dickey-Fuller tests.

Model	Lag	Test Statistic	10% Critical Value	Obs
Without Intercept	1	1.183	-1.620	2027
With Trend	1	-2.003	-3.120	2027
With Drift	1	-0.098	-1.282	2027
Without Intercept	30	1.613	-1.620	1998
With Trend	30	-1.553	-3.120	1998
With Drift	30	0.416	-1.282	1998

Notes: This table reports the augmented Dickey-Fuller test statistics that test whether daily EU allowance prices follow unit root processes. The null hypothesis is that daily EU allowance prices follow a unit root process. The sample period begins in 2013 and ends in 2020.

Under all these specifications, we fail to reject the hypothesis that daily carbon prices follow a random walk. This means that the carbon price today is the best predictor of the carbon price tomorrow. Hence, the daily percentage changes in carbon price, $\Delta EUA\%_t$, can be interpreted as an unexpected permanent change in the cost of carbon allowances.

5.2 | Do carbon prices affect stock prices?

A company that has free permits that exactly cover its regulated emissions is not affected by changes in the carbon price since it does not need to purchase any additional allowances. This simple observation, however, ignores the effect of the carbon price on a company's incentives to reduce its emissions. Companies would in theory equate their marginal cost of reducing their emissions to the carbon price on the market. If the price increases, a company could reduce its emissions, and sell free permits it no longer needs. The size of the carbon emission reduction would depend on the shape of its abatement cost curve. Also, there is likely to be an investment timing decision, given that emissions abatements are lumpy and irreversible investments, so that carbon emission reductions will not continuously react to daily changes in carbon price. A company with verified emissions that exceed its current allowances is immediately negatively affected by an increase in the carbon price, since it must purchase more allowances to comply with emissions regulations in a timescale that does not allow for emission reducing investments to be implemented. The bigger the shortfall in allowances, the higher is the cost impact of an increase in the carbon price for the company.

Given that the information on free allocations was publicly available at the installation level, it is reasonable to expect that investors were pricing in these effects. Accordingly, we expect a negative impact on the stock price following an increase in the carbon price for the companies that have a shortfall in allowances, and that this impact will be larger for a larger shortfall.

5.2.1 | Stock prices, emissions and carbon prices

We first examine whether daily stock price changes are correlated with changes in carbon prices, using $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ to capture a firm's exposure to carbon prices. We deviate from Equation 9 by not including $\text{SHORTFALL RATIO}_{it-1}$, which allows us to compare our results to the prior literature. The sample consists of firms that are regulated under the EU ETS: These firms either have a positive amount of freely allocated ETS allowances, or a positive amount of verified emissions. Table 4 reports the results.

In Column (1) we regress daily stock price changes on the interaction of $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ and the daily percentage change in carbon prices, without controlling for firm characteristics, nor market risk factors. In Column (2), we add company characteristics as controls, and in Column (3) we also include loadings on standard risk factors and stock volatility. The coefficient of $\Delta EUA\%_t$ is absorbed by the date fixed effect. Interestingly, the coefficient of the interaction term $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1}) \times \Delta EUA\%_t$ is statistically significant and positive, at 0.0036, and remains essentially unchanged under all three specifications.

These results show that there is a contemporaneous positive association between stock prices and carbon prices for companies with a higher level of freely allocated ETS allowances. Based on the estimates in Columns (1)–(3), for firms with $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ one standard deviation above the mean, a one percentage point increase in $\Delta EUA\%_t$ (3.00%) translates into a 0.036% higher stock price. This suggests that firms with a greater amount of freely allocated ETS allowances benefit from a windfall gain when carbon prices are higher, which is priced by investors. This is consistent with the findings using data in earlier Phases of the EU ETS (e.g., Mo et al., 2012; Oberndorfer, 2009; Oestreich & Tsiakas, 2015; Zhu et al., 2018).

We perform several robustness checks. First, we show that using alternative emission variables to capture the size of a firm's ETS emissions, does not affect our conclusion. Table C1 replicates Table 4. In Panel A, we use

TABLE 4 Carbon prices, emission allowances, and stock returns.

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
LOG(1 + FREE EMISSIONS _{it-1}) × ΔEUA% _t	0.0036** (0.0017)	0.0036** (0.0017)	0.0036** (0.0017)
LOG(1 + FREE EMISSIONS _{it-1})	-0.0111*** (0.0039)	-0.0133*** (0.0042)	-0.0148*** (0.0040)
LOG(ASSETS _{it-1})		-0.0360*** (0.0105)	-0.0393*** (0.0105)
TANGIBILITY _{it-1}		-0.0026 (0.0264)	-0.0040 (0.0252)
LEVERAGE _{it-1}		0.1039 (0.0633)	0.0964 (0.0638)
LOG(MV _{it-1})		0.0149 (0.0091)	0.0152 (0.0096)
LOG(M/B _{it-1})		-0.0420*** (0.0082)	-0.0439*** (0.0085)
NET INCOME _{it-1} /EQUITY _{it-2}		0.0206 (0.0214)	0.0221 (0.0207)
CASH _{it-1} /ASSETS _{it-1}		-0.0164 (0.0445)	-0.0212 (0.0437)
LOG(TURNOVER _{it-1})		0.0248*** (0.0074)	0.0251*** (0.0070)
β _{it} ^{SMB}			-0.0137 (0.0130)
β _{it} ^{HML}			-0.0043 (0.0108)
β _{it} ^{RMW}			0.0140 (0.0085)
β _{it} ^{CMA}			0.0047 (0.0077)
β _{it} ^{MKT}			-0.0230 (0.0229)
β _{it} ^{WML}			0.0034 (0.0129)
VOLATILITY _{it}			1.2496 (1.1048)

(Continues)

TABLE 4 (Continued)

	$RET_{i\tau}$ (1)	$RET_{i\tau}$ (2)	$RET_{i\tau}$ (3)
Observations	565,616	565,616	565,616
R-squared	0.2268	0.2269	0.2270
Industry FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Date FE	Yes	Yes	Yes
Cluster	Firm & Date	Firm & Date	Firm & Date
Firms	316	316	316
Adj. R^2	0.224	0.224	0.224

Notes: This table reports results from OLS panel regressions. The dependent variable is $RET_{i\tau}$, firm i 's realized stock return from day $\tau - 1$ to day τ . $\text{LOG}(1 + \text{FREE EMISSIONS}_{i\tau-1})$ is the log of one plus firm i 's freely allocated ETS emission allowances in year $t - 1$. $\Delta \text{EUA}\%_{\tau}$ is the percentage change in daily EUA closing price from day $\tau - 1$ to day τ . $\text{LOG}(\text{ASSETS}_{i\tau-1})$ is the log of firm i 's asset in year t . $\text{TANGIBILITY}_{i\tau-1}$ is firm i 's fixed asset divided by total assets in year $t - 1$. $\text{LEVERAGE}_{i\tau-1}$ is firm i 's book leverage in year $t - 1$. $\text{LOG}(\text{MV}_{i\tau-1})$ is the log of firm i 's market value on day $\tau - 1$. $\text{LOG}(\text{M}/\text{B}_{i\tau-1})$ is firm i 's market-to-book ratio on day $\tau - 1$. $\text{NET INCOME}_{i\tau-1}/\text{EQUITY}_{i\tau-2}$ is firm i 's return on equity in year $t - 1$. $\text{CASH}_{i\tau-1}/\text{ASSETS}_{i\tau-1}$ is firm i 's cash-to-asset ratio in year $t - 1$. $\text{LOG}(\text{TURNOVER}_{i\tau-1})$ is the log of firm i 's turnover (sales) for in year $t - 1$. $\beta_{i\tau}^E$ is firm i 's loading on the European Fama-French factor F on day τ , calculated using daily returns data in a 252-day window. $\text{VOLATILITY}_{i\tau}$ is firm i 's volatility on day t , i.e., calculated using daily returns data in a 252-day window. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowances or a positive amount of verified ETS emissions in year $t - 1$. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are two-way clustered at the firm and date level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

$\text{LOG}(\text{FREE EMISSIONS}_{i\tau-1})$ (i.e., the log of free emissions without adding 1 before taking logs), to examine whether adding 1 before log-linearizing the level of free emissions introduces substantial bias. In Panel B, we use $\text{LOG}(\text{VERIFIED EMISSIONS}_{i\tau-1})$, the log of verified emissions, to show that using actual emission levels instead of free permits does not affect our conclusions in any material way, as free permits and verified emissions are highly correlated in Phase 3 (and the earlier Phases). In our sample, the correlation coefficient between firm-year level verified emissions and free permits is 0.71.

Next, we address the concern that the results are driven by firms in the electricity or transportation industries, which are most affected by the EU ETS. Table C2 replicates Tables 4 and Table C1, but excluding firms in these industries. Our conclusions remain qualitatively similar.

5.2.2 | Stock prices, emissions, permit shortfall and carbon prices

While Table 4 corroborates with findings in prior literature, it fails to capture a firm's net exposure to carbon prices. Firms with insufficient free permits to cover their verified emissions are required to purchase additional permits either at auctions or in the secondary market. Given the high correlation between verified emissions and free permits in Phases 1–3, it is not surprising to find a positive correlation between carbon prices and stock prices on average, when permit shortfall is not explicitly taken into account.¹⁵ Based on our model in Section 3, firm value is

¹⁵At the firm-year level, the correlation coefficient between verified emissions and free permits is 0.71 in our sample, which spans the entire Phase 3.

increasing in carbon prices for firms with excess permits, but decreasing for firms with a permit shortfall. This implies the need to explicitly account for the proportion of verified emissions that are covered by freely allocated ETS allowances. Table 5 reports results using Equation 9, where we fully interact $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$, $\text{SHORTFALL RATIO}_{it-1}$, and $\Delta\text{EUA}\%_t$ to measure a firm's net exposure to carbon prices.

In Columns (1)–(3), the coefficient of the triple interaction term is negative and statistically significant, ranging from -0.0146 to -0.0147 . The coefficient of the interaction term between $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ and $\Delta\text{EUA}\%_t$ is statistically significant and positive, at 0.0134 across columns. The coefficient of the interaction term between $\text{SHORTFALL RATIO}_{it-1}$ and $\Delta\text{EUA}\%_t$ is statistically insignificant but negative, ranging from -0.0048 to -0.0049 .

These results lend support to our theoretical predictions. Suppose we compare two firms, both with $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ that is one standard deviation above the mean. The stock price of the firm with a $\text{SHORTFALL RATIO}_{it-1}$ of 1 (i.e., no free permits to cover verified emissions) will change by $(-0.0147\% + 0.0134\% - 0.0048\%) = -0.0061\%$. In contrast, the stock price of the firm with a $\text{SHORTFALL RATIO}_{it-1}$ of 0 (i.e., free permits are sufficient to cover verified emissions) will change by 0.0134% . Collectively, these findings suggest that firm value is increasing for firms with more free permits than their verified emissions, but decreasing for firms with a significant permit shortfall.

Our results are robust to replacing $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ with $\text{LOG}(\text{VERIFIED EMISSIONS}_{it-1})$, as shown in Table C3. The conclusion that firm value is increasing in the proportion of verified emissions covered by free permits, and decreasing if there is a permit shortfall, remains unaffected. In Table C4, we exclude firms in the electricity or transportation industries. We also replicate Table C3 by replacing $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ with $\text{LOG}(\text{VERIFIED EMISSIONS}_{it-1})$, but excluding firms in these industries. Our results are robust to these changes.

5.2.3 | Effect of the recent surge in carbon prices

The progressive reduction in freely allocated carbon emission allowances from 80% in 2013 to 30% in 2020, and the uninterrupted rise in carbon prices over the duration of Phase 3 suggest that the impact of carbon prices on company valuations materialized primarily in the later years of Phase 3. To be sure, carbon prices languished substantially below €10 per ton of CO₂ for several years. The carbon price rose significantly after 2018, however, climbing from a low of €7.62 on 8th January, 2018, to a high of €33.28 on 28th December, 2020. Given that carbon prices were very low until 2018, it is reasonable to expect that the effect of carbon pricing on company valuations only manifests itself in the last three years of Phase 3. We test this hypothesis by interacting our emission variables and $\Delta\text{EUA}\%_t$ with the sub-period indicator $\text{YEAR}_{2018-2020}$. The results are reported in Table 6.

As shown in Columns (1)–(3), the negative effect of the triple interaction term on stock prices is concentrated in the 2018–2020 sub-period only, when the economic significance of carbon prices surged. Similarly, the positive effect of $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ is only significant in this sub-period.

As a robustness check, Table C5 replicates Table 6, excluding firms in the electricity or transportation industries. We also report results using alternative variables to measure the size of a firm's ETS emissions. These analyses show that the effect of carbon prices on stock returns are primarily driven by the 2018–2020 sub-period, where carbon prices surged significantly.¹⁶

All in all, in the earlier sub-period the carbon price had no significant effect on company valuations. The carbon price was too low to have a material impact. However, when the carbon price increased four folds between 2018

¹⁶In Table C6, we report results with standard errors two-way clustered at the industry and date levels. Our key findings – that carbon prices affect stock prices based on a company's net exposure (Table 5), and that the effects are driven by the period when carbon prices became economically significant (Table 6) – remain statistically significant. However, we note that the smaller number of clusters (approximately 50 clusters) may lead to biased standard errors (see, for example, Abadie et al., 2022; Cameron & Miller, 2015).

TABLE 5 Carbon prices, emission allowances, shortfall, and stock returns.

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1} × ΔEUA% _t	-0.0147** (0.0065)	-0.0146** (0.0065)	-0.0146** (0.0065)
LOG(1 + FREE EMISSIONS _{it-1}) × ΔEUA% _t	0.0134*** (0.0050)	0.0134*** (0.0050)	0.0134*** (0.0050)
SHORTFALL RATIO _{it-1} × ΔEUA% _t	-0.0048 (0.0076)	-0.0048 (0.0076)	-0.0049 (0.0076)
LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1}	0.0074 (0.0114)	0.0224 (0.0141)	0.0189 (0.0135)
LOG(1 + FREE EMISSIONS _{it-1})	-0.0170 (0.0106)	-0.0307** (0.0125)	-0.0292** (0.0120)
SHORTFALL RATIO _{it-1}	0.0005 (0.0119)	-0.0019 (0.0117)	-0.0001 (0.0116)
LOG(ASSETS _{it-1})		-0.0337*** (0.0110)	-0.0370*** (0.0111)
TANGIBILITY _{it-1}		0.0215 (0.0282)	0.0190 (0.0272)
LEVERAGE _{it-1}		0.0660 (0.0682)	0.0650 (0.0671)
LOG(MV _{it-1})		0.0125 (0.0095)	0.0123 (0.0101)
LOG(M/B _{it-1})		-0.0432*** (0.0087)	-0.0446*** (0.0090)
NET INCOME _{it-1} /EQUITY _{it-2}		0.0279 (0.0221)	0.0283 (0.0212)
CASH _{it-1} /ASSETS _{it-1}		-0.0046 (0.0478)	-0.0103 (0.0474)
LOG(TURNOVER _{it-1})		0.0267*** (0.0078)	0.0264*** (0.0073)
β _{it} ^{SMB}			-0.0136 (0.0132)
β _{it} ^{HML}			-0.0017 (0.0111)
β _{it} ^{RMW}			0.0122 (0.0087)

TABLE 5 (Continued)

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
β_{it}^{CMA}			0.0074 (0.0078)
β_{it}^{MKT}			-0.0176 (0.0234)
β_{it}^{WML}			0.0002 (0.0132)
VOLATILITY _{it}			0.7602 (1.1960)
Observations	524,192	524,192	524,192
R-squared	0.2311	0.2312	0.2313
Industry FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Date FE	Yes	Yes	Yes
Cluster	Firm & Date	Firm & Date	Firm & Date
Firms	307	307	307
Adj. R ²	0.228	0.228	0.228

Notes: This table reports results from OLS panel regressions. The dependent variable is RET_{it} , firm i 's realized stock return from day $\tau - 1$ to day τ . $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ is the log of one plus firm i 's freely allocated ETS emission allowances in year $t - 1$. $\text{SHORTFALL RATIO}_{it-1}$ is the proportion of firm i 's verified ETS emissions not covered by freely allocated allowances in year $t - 1$. $\Delta \text{EUA}\%_{\tau}$ is the percentage change in daily EUA closing price from day $\tau - 1$ to day τ . $\text{LOG}(\text{ASSETS}_{it-1})$ is the log of firm i 's asset in year t . $\text{TANGIBILITY}_{it-1}$ is firm i 's fixed asset divided by total assets in year $t - 1$. LEVERAGE_{it-1} is firm i 's book leverage in year $t - 1$. $\text{LOG}(\text{MV}_{it-1})$ is the log of firm i 's market value on day $\tau - 1$. $\text{LOG}(M/B_{it-1})$ is firm i 's market-to-book ratio on day $\tau - 1$. $\text{NET INCOME}_{it-1}/\text{EQUITY}_{it-2}$ is firm i 's return on equity in year $t - 1$. $\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$ is firm i 's cash-to-asset ratio in year $t - 1$. $\text{LOG}(\text{TURNOVER}_{it-1})$ is the log of firm i 's turnover (sales) for in year $t - 1$. β_{it}^F is firm i 's loading on the European Fama-French factor F on day τ , calculated using daily returns data in a 252-day window. VOLATILITY_{it} is firm i 's volatility on day t , i.e., calculated using daily returns data in a 252-day window. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowances or a positive amount of verified ETS emissions in year $t - 1$. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are two-way clustered at the firm and date level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

and 2020, the effects became significant and were amplified by the difference between free emissions allowances and regulated emissions. Together, these findings indicate that carbon prices affected stock prices in an economically and statistically significant way only when the level of carbon prices increased substantially.

5.3 | Do carbon prices affect operations?

In this section, we explore whether carbon prices have affected operations. Carbon prices matter in several ways. First, companies' decisions on how much to invest in emissions reductions could be affected. Second, the extent to

TABLE 6 Carbon prices and stock returns: Effects by sub-periods.

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1} × ΔEUA% _t × YEAR _t ²⁰¹⁸⁻²⁰²⁰	-0.0325** (0.0127)	-0.0326** (0.0127)	-0.0326** (0.0127)
LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1} × ΔEUA% _t	-0.0062 (0.0061)	-0.0062 (0.0061)	-0.0062 (0.0060)
LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1} × YEAR _t ²⁰¹⁸⁻²⁰²⁰	0.0043 (0.0259)	0.0067 (0.0259)	0.0082 (0.0257)
LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1}	0.0108 (0.0147)	0.0252 (0.0177)	0.0213 (0.0169)
LOG(1 + FREE EMISSIONS _{it-1}) × ΔEUA% _t × YEAR _t ²⁰¹⁸⁻²⁰²⁰	0.0300*** (0.0113)	0.0301*** (0.0113)	0.0301*** (0.0113)
LOG(1 + FREE EMISSIONS _{it-1}) × ΔEUA% _t	0.0058 (0.0044)	0.0057 (0.0044)	0.0058 (0.0044)
SHORTFALL RATIO _{it-1} × ΔEUA% _t × YEAR _t ²⁰¹⁸⁻²⁰²⁰	-0.0072 (0.0127)	-0.0072 (0.0127)	-0.0072 (0.0127)
SHORTFALL RATIO _{it-1} × ΔEUA% _t	0.0002 (0.0071)	0.0002 (0.0071)	0.0001 (0.0071)
LOG(1 + FREE EMISSIONS _{it-1}) × YEAR _t ²⁰¹⁸⁻²⁰²⁰	-0.0151 (0.0212)	-0.0171 (0.0212)	-0.0178 (0.0211)
LOG(1 + FREE EMISSIONS _{it-1})	-0.0147 (0.0122)	-0.0280** (0.0140)	-0.0263** (0.0133)
SHORTFALL RATIO _{it-1} × YEAR _t ²⁰¹⁸⁻²⁰²⁰	0.0263 (0.0278)	0.0300 (0.0279)	0.0356 (0.0279)
SHORTFALL RATIO _{it-1}	-0.0112 (0.0147)	-0.0155 (0.0148)	-0.0160 (0.0147)
ΔEUA% _t × YEAR _t ²⁰¹⁸⁻²⁰²⁰	-0.0083 (0.0139)	-0.0083 (0.0139)	-0.0083 (0.0139)
YEAR _t ²⁰¹⁸⁻²⁰²⁰	-0.0074 (0.0336)	-0.0198 (0.0343)	-0.0204 (0.0342)
LOG(ASSETS _{it-1})		-0.0337*** (0.0111)	-0.0373*** (0.0112)
TANGIBILITY _{it-1}		0.0218 (0.0284)	0.0186 (0.0275)

TABLE 6 (Continued)

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
LEVERAGE _{it-1}		0.0697 (0.0687)	0.0700 (0.0676)
LOG(MV _{it-1})		0.0127 (0.0094)	0.0128 (0.0100)
LOG(M/B _{it-1})		-0.0439*** (0.0087)	-0.0452*** (0.0090)
NET INCOME _{it-1} /EQUITY _{it-2}		0.0319 (0.0219)	0.0326 (0.0211)
CASH _{it-1} /ASSETS _{it-1}		-0.0075 (0.0481)	-0.0136 (0.0476)
LOG(TURNOVER _{it-1})		0.0265*** (0.0079)	0.0261*** (0.0075)
β_{it}^{SMB}			-0.0141 (0.0132)
β_{it}^{HML}			-0.0016 (0.0110)
β_{it}^{RMW}			0.0128 (0.0086)
β_{it}^{CMA}			0.0069 (0.0077)
β_{it}^{MKT}			-0.0172 (0.0233)
β_{it}^{WML}			-0.0005 (0.0132)
VOLATILITY _{it}			0.8103 (1.1985)
Observations	524,192	524,192	524,192
R-squared	0.2312	0.2313	0.2314
Industry FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Date FE	Yes	Yes	Yes
Cluster	Firm & Date	Firm & Date	Firm & Date

(Continues)

TABLE 6 (Continued)

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
Firms	307	307	307
Adj. R ²	0.228	0.228	0.228

Notes: This table reports results from OLS panel regressions. The dependent variable is RET_{it} , firm i 's realized stock return from day $\tau - 1$ to day τ . $\text{LOG}(1 + \text{FREE EMISSIONS}_{it-1})$ is the log of one plus firm i 's freely allocated ETS emission allowances in year $t - 1$. $\text{SHORTFALL RATIO}_{it-1}$ is the proportion of firm i 's verified ETS emissions not covered by freely allocated allowances in year $t - 1$. $\Delta \text{EUA}\%_{\tau}$ is the percentage change in daily EUA closing price from day $\tau - 1$ to day τ . $\text{LOG}(\text{ASSETS}_{it-1})$ is the log of firm i 's asset in year t . $\text{TANGIBILITY}_{it-1}$ is firm i 's fixed asset divided by total assets in year $t - 1$. LEVERAGE_{it-1} is firm i 's book leverage in year $t - 1$. $\text{LOG}(\text{MV}_{it-1})$ is the log of firm i 's market value on day $\tau - 1$. $\text{LOG}(M/B_{it-1})$ is firm i 's market-to-book ratio on day $\tau - 1$. $\text{NET INCOME}_{it-1}/\text{EQUITY}_{it-2}$ is firm i 's return on equity in year $t - 1$. $\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$ is firm i 's cash-to-asset ratio in year $t - 1$. $\text{LOG}(\text{TURNOVER}_{it-1})$ is the log of firm i 's turnover (sales) for in year $t - 1$. β^F_{it} is firm i 's loading on the European Fama-French factor F on day τ , calculated using daily returns data in a 252-day window. VOLATILITY_{it} is firm i 's volatility on day t , i.e., calculated using daily returns data in a 252-day window. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowances or a positive amount of verified ETS emissions in year $t - 1$. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are two-way clustered at the firm and date level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

which free permits cover the firms' regulated emissions will affect both the availability of cash and the salience of carbon emissions in operations and decision making. To explore these potential effects, we investigate whether carbon prices have had a material effect on companies' operating performance, carbon emissions, investment, and research and development (R&D). Since financial and emission variables are only available at annual frequency, we estimate Equation 10, where we examine the interactive effect of the level of carbon prices ($\text{LOG}(\text{EUA}_{it})$) and the shortfall ratio. We include firm fixed effects to control for cross-sectional unobserved heterogeneity.

5.3.1 | Operating performance

The most direct economic channel through which carbon pricing can be expected to affect corporate operations is through the impact of carbon pricing on profitability. If the cost of goods sold increases because of an increase in carbon prices and/or an increase in the fraction of emissions that are subject to carbon pricing, then it is to be expected that profit margins could be affected. We explore the extent to which increases in the carbon price have affected the bottom line of companies under the EU allowance scheme. We hypothesize that firms with a significant permit shortfall have suffered financially from higher carbon prices, whereas firms with a greater permit coverage have benefited. The results are reported in Table 7.

In Column (1), the dependent variable is return on assets. We find that the coefficient of $\text{SHORTFALL RATIO}_{it-1} \times \text{LOG}(\text{EUA}_{it})$ to be -0.0152 , which is statistically significant at the 1% level. In Column (2), the dependent variable is return on equity. The coefficient of $\text{SHORTFALL RATIO}_{it-1} \times \text{LOG}(\text{EUA}_{it})$ is -0.0376 , which is statistically significant at the 5% level. To contextualize the economic magnitude of these estimates, consider two firms, one with a $\text{SHORTFALL RATIO}_{it-1}$ of 1 and another with a $\text{SHORTFALL RATIO}_{it-1}$ of 0. A one standard deviation increase in $\text{LOG}(\text{EUA}_{it})$ (0.6444) translates into a $(-0.0152 \times 0.6444) = -0.0098$ lower return on assets or a $(-0.0376 \times 0.6444) = -0.024$ lower return on equity for the firm with a $\text{SHORTFALL RATIO}_{it-1}$ of 1. Given that the mean return on assets (return on equity) in the sample is 0.0369 (0.0932), this translates into a 26.6% (25.8%) relative reduction in profitability, which is substantial.

TABLE 7 Carbon prices, shortfall ratio, and profitability.

	$\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$ (1)	$\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$ (2)
$\text{SHORTFALL RATIO}_{it-1} \times \text{LOG}(\text{EUA}_{it})$	-0.0152*** (0.0051)	-0.0376** (0.0189)
$\text{SHORTFALL RATIO}_{it-1}$	0.0280** (0.0127)	0.0748 (0.0465)
$\text{LOG}(\text{EUA}_{it})$	0.0343*** (0.0130)	0.0990** (0.0428)
$\text{LOG}(\text{ASSETS}_{it-1})$	-0.0591*** (0.0142)	-0.1140* (0.0662)
$\text{LOG}(M/B_{it-1})$	0.0225*** (0.0069)	0.1675*** (0.0495)
$\text{LOG}(MV_{it-1})$	0.0117* (0.0063)	-0.0481 (0.0451)
$\text{TANGIBILITY}_{it-1}$	-0.0279 (0.0387)	-0.0535 (0.1274)
LEVERAGE_{it-1}	-0.0563 (0.0349)	-0.2969* (0.1534)
$\text{LOG}(\text{TURNOVER}_{it-1})$	0.0251** (0.0121)	0.0966** (0.0378)
$\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$	0.0021 (0.0340)	0.0134 (0.1333)
Observations	2,070	2,070
R-squared	0.5577	0.4981
Firm FE	Yes	Yes
Year FE	Yes	Yes
Cluster	Firm	Firm
Firms	289	289
Adj. R ²	0.481	0.411

Notes: This table reports results from OLS panel regressions. In Column (1), the dependent variable is $\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$, firm *i*'s net income in year *t* - 1 scaled by beginning-of-period assets. In Column (2), the dependent variable is $\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$, firm *i*'s net income in year *t* - 1 scaled by beginning-of-period book equity. $\text{SHORTFALL RATIO}_{it-1}$ is the proportion of firm *i*'s verified ETS emissions not covered by freely allocated allowances in year *t* - 1. $\text{LOG}(\text{EUA}_{it})$ is the log of EUA price on firm *i*'s fiscal year end date in year *t*. $\text{LOG}(\text{ASSETS}_{it-1})$ is the log of firm *i*'s asset in year *t*. $\text{LOG}(M/B_{it-1})$ is firm *i*'s market-to-book ratio in year *t* - 1. $\text{LOG}(MV_{it-1})$ is the log of firm *i*'s market value in year *t* - 1. $\text{TANGIBILITY}_{it-1}$ is firm *i*'s fixed asset divided by total assets in year *t* - 1. LEVERAGE_{it-1} is firm *i*'s book leverage in year *t* - 1. $\text{LOG}(\text{TURNOVER}_{it-1})$ is the log of firm *i*'s turnover (sales) for in year *t* - 1. $\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$ is firm *i*'s cash-to-asset ratio in year *t* - 1. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowance or a positive amount of verified ETS emissions in year *t* - 1. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are clustered at the firm level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

Our findings lend support to a profitability channel, and suggest that companies are not able to completely pass on the increases in carbon prices to consumers. A number of studies discuss the role of cost pass-through, where companies are able to pass on the increases in carbon prices to consumers (see, for example, Bushnell et al., 2013; Oberndorfer, 2009; Oestreich & Tsiakas, 2015; Veith et al., 2009). Using wholesale market data on electricity prices in Spain, Fabra and Reguant (2014) find a near complete pass-through of costs to consumers. However, recent studies highlight that the evidence of full pass-through of carbon prices is mixed. Neuhoﬀ and Ritz (2019) provide an economic framework to examine the drivers behind cost pass-through in the carbon markets and cast doubt on the strength of existing evidence. Using a unique dataset covering Belgian firms in a more recent period where there was a surge in ETS prices, Martin et al. (2024) do not find a statistically significant relationship between product prices and whether a firm is in the ETS. While our findings cannot rule out partial cost pass-through, we can rule out the existence of complete cost pass-through in our setting, given that carbon prices affect company valuation and profitability.¹⁷

5.3.2 | Carbon emissions

The goal of carbon pricing is to curb carbon emissions that cause global overheating. It is therefore natural to ask what the effect of carbon prices has been on corporate carbon emissions. We have established that carbon price rises have had a negative impact on stock valuations of companies with a shortfall in allowances, and that carbon price increases have substantially affected the operating performance of these companies. This suggests that carbon pricing should have provided a strong incentive for these companies to reduce their emissions. To test whether carbon prices have affected emissions, we estimate Equation 10, with EU and global emission levels as dependent variables. Table 8 reports the results.

In Column (1) the dependent variable is $\text{LOG}(\text{VERIFIED EMISSIONS}_{it})$, the log of verified ETS emissions. The coefficient of $\text{SHORTFALL RATIO}_{it-1} \times \text{LOG}(\text{EUA}_{it})$ is -0.1970 , and is significant at the 5% level. This means that firms with a larger allowance shortfall have reduced their verified emissions in response to a rise in carbon prices. For the firms with a $\text{SHORTFALL RATIO}_{it-1}$ of 1, a one standard deviation higher $\text{LOG}(\text{EUA}_{it})$ is associated with a $(-0.1970 \times 0.6444) = 0.1269$ lower $\text{LOG}(\text{VERIFIED EMISSIONS}_{it})$. This is an encouraging finding for the EU ETS. It suggests that carbon pricing is having the desired effect, at least qualitatively. But this result begs the question of the effect on overall corporate carbon emissions, those that fall under the EU ETS, and those that do not. The listed companies that are subject to the EU ETS are likely to have other operations that do not fall under the jurisdiction of the EU ETS. Presumably, these companies can therefore substitute their activities towards subsidiaries or regions outside of the EU ETS system, whose carbon emissions are not priced.

We explore this question in Columns (2) and (3). In Column (2), the dependent variable is $\text{LOG}(\text{NET SCOPE } 1_{it})$, the log of a corporation's total scope 1 emissions (its direct emissions) less its regulated emissions under the EU ETS. These "net" Scope 1 emissions represent global non-regulated emissions by the EU. We find that the coefficient of $\text{SHORTFALL RATIO}_{it-1} \times \text{LOG}(\text{EUA}_{it})$, although negative, is statistically insignificant, suggesting that non-EU corporate emissions have not been affected by changes in the EUA price. In Column (3), the dependent variable is $\text{LOG}(\text{SCOPE } 2_{it})$, the company's total scope 2 emissions defined as indirect emissions from business operations, mostly from the purchase of non-renewable electricity. We find that the coefficient of

¹⁷The presence of a cost pass-through effect could affect sales, if other relevant portions of the production process remain the same. As a descriptive exercise, we examine the relationship between carbon prices and turnover (sales) to detect the presence of cost pass-through. If companies are able to completely pass on increases in carbon prices to consumers, we expect to see a significantly positive relationship between carbon prices and turnover. Panel A of Table C7 in the Internet Appendix shows that the level of carbon prices is not significantly associated with the log of turnover, nor with turnover scaled by total assets. Panel B of Table C7 in the Internet Appendix examines industry heterogeneity, finding weak evidence that a higher carbon price is associated with higher turnover for firms in the construction industry. This suggests that there is no evidence of an economy-wide, complete pass-through of carbon prices to consumers for our sample of firms and years.

$SHORTFALL\ RATIO_{it-1} \times LOG(EUA_{it})$ is positive and statistically significant, suggesting that some regulated firms might have replaced their self-generation of fossil-fuel based electricity to the purchase of electricity from the grid.

Given the lack of exogenous variation in both the shortfall variable and the carbon price variable, this set of results does not lend itself to a causal interpretation. However, these results reveal that the effect of EU carbon pricing is restricted to regulated emissions in the European Union. Prior literature has shown that there is limited evidence of carbon leakage in Phases 1 and 2 of the ETS. In Phase 3, we find that the same holds by comparing

TABLE 8 Carbon prices, shortfall ratio, and carbon emissions.

	LOG(VERIFIED EMISSIONS _{it}) (1)	LOG(NET SCOPE 1 _{it}) (2)	LOG(SCOPE 2 _{it}) (3)
$SHORTFALL\ RATIO_{it-1} \times LOG(EUA_{it})$	-0.1970** (0.0904)	-0.0094 (0.1164)	0.3283*** (0.1053)
$SHORTFALL\ RATIO_{it-1}$	1.0328*** (0.3040)	-0.2004 (0.2900)	-0.5804** (0.2575)
$LOG(EUA_{it})$	0.1034 (0.1691)	0.0585 (0.0960)	0.0380 (0.0819)
$LOG(ASSETS_{it-1})$	-0.0360 (0.1154)	0.4790** (0.2098)	0.0946 (0.1742)
$LOG(M/B_{it-1})$	-0.0126 (0.0711)	0.2308* (0.1349)	-0.2267* (0.1289)
$LOG(MV_{it-1})$	0.0398 (0.0950)	-0.1676 (0.1238)	0.3007** (0.1358)
$TANGIBILITY_{it-1}$	0.4176 (0.2591)	1.1089** (0.5367)	0.0328 (0.6706)
$LEVERAGE_{it-1}$	-0.4300 (0.3987)	0.3911 (0.7113)	0.3218 (0.6799)
$LOG(TURNOVER_{it-1})$	0.0150 (0.0935)	0.8148*** (0.1967)	0.4878** (0.1932)
$CASH_{it-1}/ASSETS_{it-1}$	0.3635 (0.3846)	0.1677 (0.6690)	-0.1331 (0.5315)
$NET\ INCOME_{it-1}/ASSETS_{it-2}$	0.0824 (0.2837)	-0.7473 (0.6173)	-0.6982 (0.4993)
Observations	1,622	1,622	1,622
R-squared	0.9864	0.9391	0.9363
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Cluster	Firm	Firm	Firm

(Continues)

TABLE 8 (Continued)

	LOG(VERIFIED EMISSIONS _{it}) (1)	LOG(NET SCOPE 1 _{it}) (2)	LOG(SCOPE 2 _{it}) (3)
Firms	256	256	256
Adj. R ²	0.984	0.927	0.923

Notes: This table reports results from OLS panel regressions. In Column (1), the dependent variable is LOG(VERIFIED EMISSIONS_{it}), the log of firm *i*'s verified ETS emissions in year *t*. In Column (2), the dependent variable is LOG(NET SCOPE 1_{it}), the log of firm *i*'s global scope 1 emissions minus ETS emissions in year *t*. In Column (3), the dependent variable is LOG(SCOPE 2_{it}), the log of firm *i*'s global scope 2 emissions in year *t*. *SHORTFALL RATIO*_{it-1} is the proportion of firm *i*'s verified ETS emissions not covered by freely allocated allowances in year *t* - 1. LOG(*ASSETS*_{it-1}) is the log of firm *i*'s asset in year *t*. LOG(*M/B*_{it-1}) is firm *i*'s market-to-book ratio in year *t* - 1. LOG(*MV*_{it-1}) is the log of firm *i*'s market value in year *t* - 1. *TANGIBILITY*_{it-1} is firm *i*'s fixed asset divided by total assets in year *t* - 1. *LEVERAGE*_{it-1} is firm *i*'s book leverage in year *t* - 1. LOG(*TURNOVER*_{it-1}) is the log of firm *i*'s turnover (sales) for in year *t* - 1. *CASH*_{it-1}/*ASSETS*_{it-1} is firm *i*'s cash-to-asset ratio in year *t* - 1. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowances or a positive amount of verified ETS emissions in year *t* - 1, and with non-missing LOG(VERIFIED EMISSIONS_{it}) or LOG(NET SCOPE 1_{it}). The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are clustered at the firm level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

emissions of listed firms: the EU carbon price is negatively associated with regulated emissions by the EU ETS for firms with a significant permit shortfall, but there is no effect on non-EU scope 1 emissions. We find some weak evidence of an increase in global scope 2 emissions, highlighting the potential for regulatory arbitrage in a regional cap-and-trade system.

5.3.3 | Investment and innovation

How did carbon prices affect incentives for firms to transition to less polluting technologies? To examine this question, we look at capital expenditures and research and development expenses. If increases in the carbon price induce firms to invest in less polluting technologies, then we expect the coefficient of *SHORTFALL RATIO*_{it-1} × LOG(*EUA*_{it}) to be positive and significant. Small changes in price, however, are unlikely to sway investment decisions if investment in green technologies is lumpy and irreversible. There is a real option embedded in the investment decision in this case and small changes in carbon price will not induce the firm to act unless the carbon price is near the strike price that triggers investment. The effect of changes in carbon price on investment is therefore likely to depend on the level of the carbon price. Table 9 reports the results of the regression linking capital expenditures to carbon prices.

In Column (1), where the dependent variable is *CAPX*_{it}/*ASSETS*_{it-1}, we find that the coefficient of *SHORTFALL RATIO*_{it-1} × LOG(*EUA*_{it}) is statistically insignificant. However, in Column (2), where the dependent variable is *R & D*_{it}/*ASSETS*_{it-1}, we find that the coefficient of *SHORTFALL RATIO*_{it-1} × LOG(*EUA*_{it}) is 0.0016, and is statistically significant at the 5% level. This suggests that while we do not find any evidence that firms with a larger permit shortfall increase capital expenditures in response to higher carbon prices, there might be some positive effects on research and development expenditures. Colmer et al. (2025) found that regulated firms in France increased their capital in Phase 2. The lack of an effect of carbon prices on investment during Phase 3 could possibly be due to the fact that regulated firms have already made investments before 2013.

All in all, our results on the direct effects of carbon pricing are that higher carbon prices have lowered operating performance for firms with a permit shortfall, which suggests that carbon prices do provide incentives for firms to lower emission levels in the EU. This is true when the price is sufficiently high and when firms do not receive allowances for free.

5.4 | Alternative hypothesis: Credit channel

A number of recent studies point to a possible credit channel (see, for example, Bruno & Lombini, 2023; Tran & Uzmanoglu, 2024). If investors' environmental attention affects funding conditions in the credit market, firms with a higher leverage may have an amplified response in valuation and profitability to changes in carbon prices. Consistent with this hypothesis, our analyses in Table 7 find that leverage has some significant effects on profitability. To further examine the role of the credit channel, we perform two tests.

TABLE 9 Carbon prices, shortfall ratio, and investment.

	$\frac{CAPX_{it}}{ASSETS_{it-1}}$ (1)	$\frac{R\&D_{it}}{ASSETS_{it-1}}$ (2)
SHORTFALL RATIO _{it-1} × LOG(EUA _{it})	-0.0023 (0.0138)	0.0016** (0.0008)
SHORTFALL RATIO _{it-1}	-0.0109 (0.0377)	-0.0037* (0.0020)
LOG(EUA _{it})	-0.0127 (0.0191)	0.0003 (0.0007)
LOG(ASSETS _{it-1})	-0.2171*** (0.0354)	-0.0074*** (0.0021)
LOG(M/B _{it-1})	0.0012 (0.0215)	-0.0010 (0.0011)
LOG(MV _{it-1})	0.0324 (0.0244)	0.0009 (0.0011)
TANGIBILITY _{it-1}	-0.0014 (0.1038)	0.0030 (0.0040)
LEVERAGE _{it-1}	0.0062 (0.0900)	-0.0045 (0.0040)
LOG(TURNOVER _{it-1})	0.0411 (0.0319)	0.0034*** (0.0013)
CASH _{it-1} /ASSETS _{it-1}	0.4639*** (0.0925)	0.0073 (0.0056)
NET INCOME _{it-1} /ASSETS _{it-2}	0.1231* (0.0746)	-0.0067 (0.0049)
Observations	2,070	2,070
R-squared	0.3349	0.9198
Firm FE	Yes	Yes
Year FE	Yes	Yes
Cluster	Firm	Firm

(Continues)

TABLE 9 (Continued)

	$\frac{CAPX_{it}}{ASSETS_{it-1}}$ (1)	$\frac{R\&D_{it}}{ASSETS_{it-1}}$ (2)
Firms	289	289
Adj. R ²	0.219	0.906

Notes: This table reports results from OLS panel regressions. In Column (1), the dependent variable is $\frac{CAPX_{it}}{ASSETS_{it-1}}$, firm *i*'s capital expenditures in year *t* scaled by total assets in year *t* – 1. In Column (2), the dependent variable is $\frac{R\&D_{it}}{ASSETS_{it-1}}$, firm *i*'s R&D expenditures in year *t* scaled by total assets in year *t* – 1. $SHORTFALL\ RATIO_{it-1}$ is the proportion of firm *i*'s verified ETS emissions not covered by freely allocated allowances in year *t* – 1. $LOG(ASSETS_{it-1})$ is the log of firm *i*'s asset in year *t*. $LOG(M/B_{it-1})$ is firm *i*'s market-to-book ratio in year *t* – 1. $LOG(MV_{it-1})$ is the log of firm *i*'s market value in year *t* – 1. $TANGIBILITY_{it-1}$ is firm *i*'s fixed asset divided by total assets in year *t* – 1. $LEVERAGE_{it-1}$ is firm *i*'s book leverage in year *t* – 1. $LOG(TURNOVER_{it-1})$ is the log of firm *i*'s turnover (sales) for in year *t* – 1. $CASH_{it-1}/ASSETS_{it-1}$ is firm *i*'s cash-to-asset ratio in year *t* – 1. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowance or a positive amount of verified ETS emissions in year *t* – 1. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are clustered at the firm level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

First, we examine whether financial leverage explains cross-sectional heterogeneity in our main results. To this end, we use the firm-day sample, and add firm *i*'s book leverage in year *t* – 1, $LEVERAGE_{it-1}^{STANDARDIZED}$, standardized by subtracting the sample mean then dividing by the sample standard deviation. We interact this variable with $LOG(1 + FREE\ EMISSIONS_{it-1})$, $SHORTFALL\ RATIO_{it-1}$ and $\Delta EUA\%_t$. Table 10 reports the results. We do not find any statistically significant effect of cross-sectional variations in leverage, based on this quadruple interaction term.

Second, we examine whether financial leverage explains cross-sectional heterogeneity in profitability. To this end, we use the firm-year sample and fully interact $LEVERAGE_{it-1}^{STANDARDIZED}$ with $SHORTFALL\ RATIO_{it-1}$ and $LOG(EUA_t)$. Table 11 reports these results. While the triple interaction term is negative, it is not significant. In an alternative specification, we use the indicator variable $HIGHLEVERAGE_{it-1}$ to capture firm leverage: it takes a value of one if firm *i*'s book leverage is above the sample median. Statistical significance increases, but it is still below conventional significance levels.

Our analyses therefore suggest that the credit channel—based on cross-sectional heterogeneity in a firm's financial leverage—is not a primary driver of our main findings. We note, however, that the profitability channel and credit channel are not mutually exclusive. We leave the opportunity to thoroughly investigate the role of the credit channel for future research.

6 | CONCLUSION

This paper studies how carbon pricing affects corporate financial performance during Phase 3 of the EU ETS, when carbon prices increased sufficiently to become material. Our empirical setting exploits differences in regulated emission levels and free emission allowance allocations across emitting firms. A first major contribution of our study is to precisely determine the net exposure to EU carbon prices of listed companies by identifying which installations are subject to the EU ETS and computing the emission allowance shortfall or surplus of each company. Precise measures of firm-specific carbon price exposures have been lacking in prior studies but our findings reveal that the relation between carbon prices and stock prices is crucially dependent on these exposures. Indeed, our key finding is that if a company has a shortfall in emission permits then an increase in the EU carbon price is associated with a decline in its stock price, but if the company has a surplus in emission permits then the increase in the EU carbon price is associated with an increase in its stock price. These relationships between carbon price and stock price are

TABLE 10 Carbon prices, emission allowances, shortfall, leverage and stock returns.

	RET _{it} (1)	RET _{it} (2)	RET _{it} (3)
LEVERAGE _{it-1} ^{STANDARDIZED} × LOG(1 + FREE EMISSIONS _{it-1}) × SHORTFALL RATIO _{it-1} × ΔEUA% _τ	0.0010 (0.0067)	0.0010 (0.0067)	0.0010 (0.0067)
Fully Interacted	Yes	Yes	Yes
Controls	No	Firm Financials	Firm Financials & Factor Loadings
Observations	524,192	524,192	524,192
R-squared	0.2311	0.2312	0.2313
Industry FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Date FE	Yes	Yes	Yes
Cluster	Firm & Date	Firm & Date	Firm & Date
Firms	307	307	307
Adj. R ²	0.228	0.228	0.228

Notes: This table reports results from OLS panel regressions. The dependent variable is RET_{it}, firm *i*'s realized stock return from day $\tau - 1$ to day τ . LOG(1 + FREE EMISSIONS_{it-1}) is the log of one plus firm *i*'s freely allocated ETS emission allowances in year $t - 1$. SHORTFALL RATIO_{it-1} is the proportion of firm *i*'s verified ETS emissions not covered by freely allocated allowances in year $t - 1$. ΔEUA%_τ is the percentage change in daily EUA closing price from day $\tau - 1$ to day τ . LEVERAGE_{it-1}^{STANDARDIZED} is firm *i*'s book leverage in year $t - 1$, standardized by subtracting the sample mean then dividing by the sample standard deviation. Coefficients of the other variables are suppressed for brevity. Firm financial controls include: LOG(ASSETS_{it-1}) is the log of firm *i*'s asset in year t . TANGIBILITY_{it-1} is firm *i*'s fixed asset divided by total assets in year $t - 1$. LEVERAGE_{it-1} is firm *i*'s book leverage in year $t - 1$. LOG(MV_{it-1}) is the log of firm *i*'s market value on day $\tau - 1$. LOG(M/B_{it-1}) is firm *i*'s market-to-book ratio on day $\tau - 1$. NET INCOME_{it-1}/EQUITY_{it-2} is firm *i*'s return on equity in year $t - 1$. CASH_{it-1}/ASSETS_{it-1} is firm *i*'s cash-to-asset ratio in year $t - 1$. LOG(TURNOVER_{it-1}) is the log of firm *i*'s turnover (sales) for in year $t - 1$. Factor loadings include: β_{it}^F is firm *i*'s loading on the European Fama-French factor *F* on day τ , calculated using daily returns data in a 252-day window. VOLATILITY_{it} is firm *i*'s volatility on day t , i.e., calculated using daily returns data in a 252-day window. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowances or a positive amount of verified ETS emissions in year $t - 1$. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are two-way clustered at the firm and date level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

significant during the years when the carbon price approached €30 for a ton of CO₂. Our second main finding is that while firms with a significant shortfall in emission permits do lower their regulated emissions in the EU, they do not lower their emissions globally.

Overall our findings are that the EU ETS has achieved the qualitatively desired effects during Phase 3 of creating incentives to limit carbon emissions within the European Union. Earlier studies for Phases 1 (2005–2007) and 2 (2008–2012) have found largely inconclusive evidence on the effects of carbon pricing, but these were largely experimentation phases with in retrospect overly generous allocations of free carbon emission allowances in the context of a global financial crisis. Carbon prices have risen sharply in the later years of Phase 3. They have become material. So much so that carbon prices had a significant negative effect on the stock price of firms with permit shortfalls in the 2018–2020 period of Phase 3. We also find that the firms with a permit shortfall have seen

TABLE 11 Carbon prices, shortfall ratio, leverage, and profitability.

	$\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$ (1)	$\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$ (2)	$\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$ (3)	$\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$ (4)
$\text{LEVERAGE}_{it-1}^{\text{STANDARDIZED}} \times \text{SHORTFALL RATIO}_{it-1} \times \text{LOG(EUA}_{it})$	-0.0033 (0.0072)	-0.0261 (0.0294)		
$\text{LEVERAGE}_{it-1}^{\text{STANDARDIZED}} \times \text{SHORTFALL RATIO}_{it-1}$	0.0166 (0.0156)	0.0822 (0.0674)		
$\text{LEVERAGE}_{it-1}^{\text{STANDARDIZED}} \times \text{LOG(EUA}_{it})$	0.0008 (0.0025)	0.0053 (0.0078)		
$\text{LEVERAGE}_{it-1}^{\text{STANDARDIZED}}$	-0.0068 (0.0050)	-0.0332* (0.0184)		
$\text{HIGH LEVERAGE}_{it-1} \times \text{SHORTFALL RATIO}_{it-1} \times \text{LOG(EUA}_{it})$			-0.0098 (0.0099)	-0.0562 (0.0352)
$\text{HIGH LEVERAGE}_{it-1} \times \text{SHORTFALL RATIO}_{it-1}$			0.0386 (0.0236)	0.1905** (0.0852)
$\text{HIGH LEVERAGE}_{it-1} \times \text{LOG(EUA}_{it})$			0.0019 (0.0045)	0.0157 (0.0148)
$\text{HIGH LEVERAGE}_{it-1}$			-0.0108 (0.0100)	-0.0475 (0.0330)
$\text{SHORTFALL RATIO}_{it-1} \times \text{LOG(EUA}_{it})$	-0.0138*** (0.0053)	-0.0370* (0.0205)	-0.0089 (0.0070)	-0.0042 (0.0250)
$\text{SHORTFALL RATIO}_{it-1}$	0.0247* (0.0132)	0.0715 (0.0497)	0.0045 (0.0176)	-0.0377 (0.0666)
$\text{LOG(EUA}_{it})$	0.0336** (0.0130)	0.0966** (0.0428)	0.0320** (0.0133)	0.0834* (0.0436)
$\text{LOG(ASSETS}_{it-1})$	-0.0593*** (0.0142)	-0.1136* (0.0661)	-0.0587*** (0.0142)	-0.1131* (0.0661)
$\text{LOG(M/B}_{it-1})$	0.0222*** (0.0069)	0.1675*** (0.0491)	0.0228*** (0.0069)	0.1689*** (0.0489)
$\text{LOG(MV}_{it-1})$	0.0113* (0.0062)	-0.0501 (0.0446)	0.0109* (0.0063)	-0.0517 (0.0449)
$\text{TANGIBILITY}_{it-1}$	-0.0293 (0.0388)	-0.0548 (0.1275)	-0.0258 (0.0392)	-0.0486 (0.1284)
$\text{LOG(TURNOVER}_{it-1})$	0.0251** (0.0121)	0.0971** (0.0381)	0.0252** (0.0121)	0.0979** (0.0384)
$\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$	0.0005 (0.0340)	0.0106 (0.1349)	-0.0003 (0.0339)	0.0059 (0.1328)

TABLE 11 (Continued)

	$\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$ (1)	$\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$ (2)	$\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$ (3)	$\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$ (4)
LEVERAGE_{it-1}			-0.0388 (0.0393)	-0.3187 (0.2059)
Observations	2,070	2,070	2,070	2,070
R-squared	0.5588	0.4992	0.5594	0.5007
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Cluster	Firm	Firm	Firm	Firm
Firms	289	289	289	289
Adj. R ²	0.481	0.411	0.482	0.413

Notes: This table reports results from OLS panel regressions. In Columns (1) and (3), the dependent variable is $\frac{\text{NET INCOME}_{it}}{\text{ASSETS}_{it-1}}$, firm i 's net income in year $t - 1$ scaled by beginning-of-period assets. In Columns (2) and (4), the dependent variable is $\frac{\text{NET INCOME}_{it}}{\text{EQUITY}_{it-1}}$, firm i 's net income in year $t - 1$ scaled by beginning-of-period book equity. $\text{LEVERAGE}_{it-1}^{\text{STANDARDIZED}}$ is firm i 's book leverage in year $t - 1$, standardized by subtracting the sample mean then dividing by the sample standard deviation. $\text{HIGHLEVERAGE}_{it-1}$ is an indicator variable that takes a value of one if firm i 's book leverage is above the sample median. $\text{SHORTFALL_RATIO}_{it-1}$ is the proportion of firm i 's verified ETS emissions not covered by freely allocated allowances in year $t - 1$. $\text{LOG}(\text{EUA}_{it})$ is the log of EUA price on firm i 's fiscal year end date in year t . $\text{LOG}(\text{ASSETS}_{it-1})$ is the log of firm i 's asset in year t . $\text{LOG}(M/B_{it-1})$ is firm i 's market-to-book ratio in year $t - 1$. $\text{LOG}(MV_{it-1})$ is the log of firm i 's market value in year $t - 1$. $\text{TANGIBILITY}_{it-1}$ is firm i 's fixed asset divided by total assets in year $t - 1$. LEVERAGE_{it-1} is firm i 's book leverage in year $t - 1$. $\text{LOG}(\text{TURNOVER}_{it-1})$ is the log of firm i 's turnover (sales) for in year $t - 1$. $\text{CASH}_{it-1}/\text{ASSETS}_{it-1}$ is firm i 's cash-to-asset ratio in year $t - 1$. Variables are winsorized at the 1% and 99% levels. The sample consists of listed firms in ETS-participating countries with a positive amount of freely allocated ETS emission allowance or a positive amount of verified ETS emissions in year $t - 1$. The sample period begins in 2013 and ends in 2020. Industry is defined by 2-digit NACE codes. Standard errors are clustered at the firm level. ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

their profitability eroded following carbon price increases, while firms without a permit shortfall have seen an increase in their profitability. Finally, we found evidence that companies with a significant allowance shortfall have reduced their regulated emissions in response to a rise in carbon prices.

Although our findings are qualitatively consistent with basic economic predictions, the quantitative effects of carbon pricing are somewhat small. The effects on company valuations have been small and the effects on carbon emission reductions have also been small. The conclusions emerging from these findings are thus that: 1) firms do appear to have the financial capacity to absorb even higher carbon prices, and 2) higher carbon prices may be required to bring about the much larger carbon emission reductions needed to achieve the 2050 net zero targets of the European Union.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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