Unveiling the Global Ripples: How EU ETS Influences Chinese Exporters

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Abstract This paper investigates the spillover effects of the European Union Emissions Trading System (EU ETS) on Chinese export firms, with a particular emphasis on a previously under-explored channel: global import-export linkages. Using a Shift-Share instrumental variable strategy, we find that increases (decreases) in EU ETS prices lead to significant rises (drops) in both export volume and value, while average export prices remain largely unchanged. These results suggest that the spillover operates primarily through quantity adjustment, consistent with changes in relative competitiveness. We further decompose the aggregate export response into within-firm, between-firm, and entry/exit components, and find that the within-firm margin accounts for the majority of the overall effect. Heterogeneity analysis reveals that firms with higher productivity, stronger financial capacity, and larger scale exhibit more pronounced responses. Counterfactual analyses based on back-of-the-envelope calculations further confirm that EU ETS shocks significantly shape China's export patterns. The decomposition of counterfactual scenarios shows that uncertainty in EU ETS prices exerts an even larger effect, discouraging firms to adjust their export ratio. At the same time, the Matthew effects weakens due to the decrease of EU ETS price in reality. Finally, we construct a general equilibrium model to rationalize the empirical findings. EU ETS's carbon price mainly affects Chinese exporters through changes in the equilibrium price index of the destination market, generating the global "ripple effect".

Keywords: EU ETS, Spillover Effect, Carbon Leakage

1 Introduction

Greenhouse-gas (GHG) emissions represent a classic global market failure and underpin the rationale for climate policy, which primarily relies on two tools: market-based instruments and command-and-control regulations. Market-based approaches, such as the EU ETS, curb emissions cost-effectively by pricing carbon and allowing firms flexibility in compliance (Pigou, 1920; Nordhaus, 1977). However, this flexibility can induce "carbon-leakage", as regulated firms relocate carbon-intensive production stages to unregulated jurisdictions or market segments. Leakage undermines mitigation efforts, reshapes global production networks, and can erode the welfare gains from unilateral policies. Thus, rigorous assessment of emissions-trading programs must consider not only domestic effects but also international spillovers (broader cross-border impacts beyond direct production or FDI relocation). Although a growing body of literature documents the direct impacts of such programs—lower emissions, greater R&D, and faster adoption of abatement technologies, and various indirect effects, including changes in firm performance and evidence of pollutant leakage (Calel and Dechezleprêtre, 2016; Bartram et al., 2022; Dechezleprêtre et al., 2023; Colmer et al., 2024), existing literature predominantly focuses on covered regions or leakage through production or FDI relocation, leaving broader spillover consequences largely unresolved.

While studies on other policies identify spillovers,[1] most EU ETS research finds no significant spillovers. For example, Colmer et al. (2024) find no differences between regulated and matched unregulated firms across several outsourcing margins, and Borghesi et al. (2020) show limited effects on FDI, except in a few highly trade-exposed sectors. These findings rely on firm-level comparisons within countries or within the EU, overlooking the price effects that propagate across regulated industries and beyond regional borders. Our paper introduces a general equilibrium framework and detailed empirical specifications to capture such price changes and reveals the importance of global trade linkages. Therefore, our paper fills this gap by examining the EU ETS, the world's first and largest market-based climate policy, and tracing its spillover effects through a previously under-explored channel: global import-export linkages.

The EU ETS provides an ideal empirical setting for two key reasons. First, its unparalleled scale and long-standing operation make it uniquely informative: the scheme currently covers more than 12,000 power plants and industrial facilities in 31 European countries, regulating approximately 45 percent of EU emissions and about 5 percent of global emissions (Colmer et al., 2024). Second, the program's cap-and-trade design generates substantial temporal and cross-sectoral variation in allowance prices, providing the identifying variation necessary to study the effects of the policy. In this Pan-European carbon market, firms facing allowance deficits purchase permits from firms with surpluses, which create explicit

[1] E.g., financially constrained firms shift emissions from California to other states (Bartram et al., 2022), and Kyoto commitments increased carbon-intensive imports (Aichele and Felbermayr, 2015)

price signals. Leveraging detailed firm–product–destination–year data on trade flows and creating a general equilibrium model, we examine how the fluctuations of carbon prices in this large carbon market reverberate through international trade networks, extending beyond the emissions of regulated European facilities.

Our empirical work incorporates three aspects. First, we examine whether emissions trading schemes implemented in a specific region (e.g., the EU ETS) generate carbon leakage via international trade. In doing so, we broaden the understanding of cross-border spillovers of climate policy. Second, we explore the heterogeneous responses of firms, showing that firms with tighter financial constraints, relatively low productivity, and small size can't adjust their export behaviors quickly and respond less to such external shocks. This helps to explain some of the mixed findings in the literature regarding the performance effects of the EU ETS. Third, we aggregate firm-level effects to the macro level and employ a combination of empirical analysis, back-of-the-envelope calculations, and decomposition techniques to assess the overall impact. We find that within-firm adjustments dominate the observed export changes, whereas between-firm reallocation and entry/exit margins contribute negligibly. Meanwhile, the fluctuations of EU ETS price dominate the within-firm effect and cause firms to decrease their export ratio to the EU market significantly.

To rationalize our empirical findings, we develop a theoretical general equilibrium model that captures the underlying spillover mechanism operating through international trade. Following Chaney (2008), we construct a multi-country, multi-industry general equilibrium framework. To incorporate carbon prices into the model, we assume two kinds of goods in the economy and incorporate a "dirty" input to bring carbon prices into our model. In this setup, differentiable goods are produced asymmetrically in all countries and traded in the world, using labor and a "dirty" input, for example, fossil energy, while homogeneous goods only need labor and serve as the numeraire. On the demand side, we assume consumers derive CES utility from both homogeneous and differentiated goods. On the supply side, we impose monopolistic competition among producers of differentiated goods, who are heterogeneous in productivity. Trade costs vary by destination, and firms' production costs are determined by the factor prices in their country of origin. Consequently, input prices, specifically those of labor and dirty inputs, enter firms' cost functions, such that a higher carbon price raises production costs for firms operating in regulated markets.

After introducing several standard assumptions following Chaney (2008), we solve this general equilibrium model and derive the exports value from country i to country j by an individual firm with productivity φ_{ij}, the export productivity threshold $\bar{\varphi}_{ij}$ and aggregate output Y_j.[2] The model reveals that

[2] Key assumptions are as follows. First, the total mass of potential entrants is proportional to the total wealth of the countries, with a redistribution of the global profits. Second, we assume a Cobb-Douglas production function for differentiated goods to simplify the calculation but all the theorems hold in more general case like CES setting. Third, each worker owns w_n shares of a global fund, which collects profits, carbon rents and tariffs from all firms and

the only channel of the spillover effect is via the aggregate price index of the regulated (EU) market. That is, higher carbon prices do not directly alter foreign firms' pricing strategies. Instead, they increase local production costs and final goods prices in the EU, thereby raising the EU's price index. This shift indirectly affects exports from unregulated regions by altering relative competitiveness. Intuitively, as carbon prices rise within the EU, demand for foreign goods increases due to the relative price advantage, while production costs in foreign countries remain unchanged. Hence, the spillover effect originates from the demand side, driven by shifts in relative prices induced by carbon regulation.

Our analysis is closely related to several strands of literature that examine the interaction between environmental regulation, international trade, and firm behavior. A primary line of inquiry focuses on the effects of the EU ETS on regulated European firms. Early studies suggest EU carbon prices can affect electricity firms' stock returns, depending on cost pass-through (e.g., Oberndorfer, 2009), while others find more ambiguous outcomes (Commins et al., 2011; Verde, 2020; Martin et al., 2014; Dechezleprêtre et al., 2023). For example, Dechezleprêtre et al. (2023) show that the EU ETS led to significant emissions reductions without adversely affecting firms' revenues or investment significantly, suggesting potential innovation-driven gains. However, contrasting findings highlight potential downsides: Commins et al. (2011) shows energy taxes increased total factor productivity and returns to capital but decreased employment, with a mixed effect on investment. The author also highlight the great heterogeneity in different sectors. These conflicting conclusions partly reflect methodological heterogeneity but also point to unresolved questions regarding the mechanisms through which carbon pricing affects firm performance, whether via cost pressures, innovation incentives, or strategic reallocation. We contribute to this debate by focusing on cross-border transmission: specifically, how EU climate regulation, through demand side channels, affects firms in non-EU countries, especially those embedded in international trade.

The second strand of literature focuses on the relationship between environmental regulation and international trade, with most studies concentrating on the consequences of such regulations—particularly trade diversion and the "pollution haven" effect (PHE) (Copeland and Taylor, 1994). For instance, Ederington et al. (2005) finds that while the average impact of environmental regulation is small, pollution-abatement costs (PAC) significantly increase imports from countries with lax regulations in pollution-intensive industries characterized by high mobility (i.e., "footloose" industries). To address potential biases in PHE estimation, including simultaneity between PAC and trade flows, aggregation bias, unobserved heterogeneity, endogenous regulation, and spatial spillovers, Levinson and Taylor (2008); Millimet and Roy (2016) develop rigorous identification strategies. Their findings consistently show that stricter state-level environmental regulation in the U.S. increases net imports and discourages inbound foreign di-

redistributes them in units of the numeraire good to its shareholders. Fourth, we assume heterogeneous productivity, fixed costs, and variable costs for firms, as commonly assumed in the literature rect investment (FDI) in pollution-intensive sectors. Similarly, Aichele and Felbermayr (2015) documents an 8% rise in such imports among Kyoto Protocol signatory countries. The study most closely related to ours is Cherniwchan and Najjar (2022), which examines how air quality standards affect exporters. They develop a simple theoretical model and leverage quasi-experimental variation to test its predictions, finding that regulation significantly alters the export behavior of the most affected manufacturers: it reduces their export volumes by 36% and increases their exit likelihood by 5%. However, this work has two key limitations relevant to our study: first, it only analyzes the impact of Canadian air quality regulations on Canadian firms, leaving room to explore the international spillover effects of environmental regulations; second, it focuses on air quality standards rather than carbon emission regulations, which is the core of our analysis.

This gap naturally leads to the third strand of literature we review, which examines the spillover effects of ETS. The empirical evidence is mixed for EU ETS is mixed and most research finds no significant spillover impact. While some evidence indicates a modest decline in employment and capacity among regulated French firms (Wagner et al., 2014), most empirical studies find little support for carbon leakage under the EU ETS. Broadly, the literature finds that the regulation does not hurt the firms' competitiveness significantly compared with unregulated firms, suggesting no substantial distortions in output (Abrell et al., 2011; Dechezleprêtre et al., 2023; Colmer et al., 2024). More specifically, the literature test the FDI channel and emission channels. In the FDI channel, Borghesi et al. (2020) observe that Italian manufacturing firms under the EU ETS did not significantly increase FDI, except in a few highly trade-exposed sectors. Nils aus dem Moore et al. (2019) find negligible evidence of significant asset relocation out of the EU due to the policy. Regarding emissions shifts, Colmer et al. (2024) use the matching Difference-in-Difference method, test three potential channels including outsourcing, product market switching, and within-firm relocation and do not identify meaningful carbon leakage. Likewise, Naegele and Zaklan (2019) use the GTAP model to analyse this problem and find no significant carbon leakage in manufacturing sectors during the EU ETS's first phases. Proposed explanations include the relatively small additional costs imposed by EU emissions policy, free permit allocations, limited stringency of early-phase carbon prices, and strategic expectations about future global regulation (Martin et al., 2014, 2016; Naegele and Zaklan, 2019).

In contrast to the largely muted responses in the EU, carbon leakage has been documented in other policy contexts, findings that motivate our focus on spillover dynamics in developing economies, particularly China. Aichele and Felbermayr (2015) find that commitments under the Kyoto Protocol, a precursor to the EU ETS, increased imports of carbon-intensive goods from non-committed countries by approximately 8%, suggesting some substitution of domestic production with foreign imports. In the

U.S., Bartram et al. (2022) show that financially constrained firms subject to California's cap-and-trade program shifted emissions-intensive activities to less regulated states, reflecting within-country leakage driven by credit constraints. Additionally, firm-level interviews highlighted that energy-intensive multinationals sometimes opted to expand capacity in non-EU countries, partially due to carbon cost concerns (Sato and Dechezleprêtre, 2015).

Evidence from China, however, remains mixed. On one hand, Cui et al. (2021) report no significant leakage under China's pilot ETS. On the other hand, Chen et al. (2025) show that large manufacturing conglomerates responded to energy regulations by reallocating production to unregulated affiliates rather than improving energy efficiency, implying leakage within corporate groups. Beyond such cost-based responses, recent studies also document more strategic adjustments. Shi and Xu (2018) and Liu et al. (2024) show that Chinese exporters exposed to the EU ETS significantly increased their green patenting and shifted their product mix towards low-carbon goods, suggesting that foreign regulation may stimulate green innovation via market-based channels. Our study builds on this perspective by focusing on the spillover effect via international trade linkages, exploring how leakage can manifest not only through physical relocation but also through product reorientation.

Our contribution is threefold. First, we analyze spillover effects from a distinct non-EU perspective. Existing empirical studies on the EU ETS predominantly rely on firm-level data within the EU to deduce spillovers, thereby confining analysis to the regulatory bloc itself. In contrast, we draw on China's comprehensive customs transaction data, as the world's largest exporter and a key EU trading partner, to isolate and quantify the EU ETS's exogenous spillover effects on a major economy outside the regulated area. Specifically, this approach allows us to quantify how EU carbon pricing reshapes trade patterns for a major economy outside the regulatory bloc.

Second, we investigate a relatively underexplored transmission mechanism. Most carbon leakage research is framed within the pollution-haven paradigm, focusing on plant relocation or FDI decisions. These studies mainly utilize detailed EU firm-level data in difference-in-differences or matching-DID settings, overlooking potential spillover effects stemming from general equilibrium effects. We instead shift the analytical focus to the international trade transmission mechanism and construct a general equilibrium model incorporating carbon prices. We document how relative cost changes induced by the EU ETS propagate through global price signals and alter competitive dynamics in destination markets. This price-mediated channel complements existing literature by highlighting trade diversion effects distinct from physical production relocation.

Third, we provide more granular empirical evidence and insightful counterfactual analysis by integrating carbon price volatility with a shift-share instrumental variables (SSIV) approach and back-of-the-envelope calculations. Earlier evaluations often employ difference-in-differences or matching methods, thereby overlooking the substantial time-series variation in carbon prices. Using highly disaggregated firm-product-destination-year data, we implement an SSIV strategy that quantifies firm-level exposure by aggregating detailed product-destination trade flows. This approach leverages the rich dynamic features of EU ETS pricing to reveal how carbon allowance price fluctuations propagate through international trade networks at a granular level. Furthermore, based on the specification, we show that if the EU ETS price had remained at its 2008 peak, total export value would have increased by 10.8%. Price fluctuations contribute substantially to the within-firm decrease.

The rest of the article is organized as follows. Section 2 introduces the institutional design of the EU ETS, data, stylized facts, variables and summary statistics. Section 3 presents the empirical methodology, while Section 4 reports the core findings. Section 5 provides quantitative assessments, followed by a conceptual theoretical framework in Section 6. The study concludes with policy implications in Section 7.

2 Institutional background, data and stylized facts

2.1 Institutional Background

Ellerman et al. (2016) outline the EU ETS's history and structure, and we draw on their work to briefly contextualize its institutional background. The EU ETS is a classic cap-and-trade system, in which the aggregate emissions of a specified set of plants is limited, while trading of implied emission reductions is allowed among these plants in order to minimize cost. Such trading is conducted through the purchase and sale of allowances, which are issued in an amount equal to the aggregate cap. *The Green Paper on Greenhouse Gas Emissions Trading within the European Union* was the first clear signal that the EU might implement an emissions trading system. The green paper also laid out the essential features of the system: a trial period to run from 2005 through 2007, followed by full implementation over the 5-year period corresponding to the First Commitment Period of the Kyoto Protocol (KP hereafter, 2008–2012). Following extensive debate, the ETS Directive was unanimously adopted by the European Council of Member States in October 2003 (OJEU 2003). And, as initially proposed in the Green Paper, the EU ETS went into effect on January 1, 2005.

The EU ETS covered electric utilities, major industrial sectors, and all domestic airline emissions in the EU's 28 member states, plus three members of the closely associated European Economic Area: Norway, Iceland, and Liechtenstein. CO_2 and some other GHGs are included in the system. As for the plant level, participation in the EU ETS is mandatory for combustion installations with a rated thermal input of 20 megawatts (MW) or more. This concerns fossil-fuel fired power plants, as well as

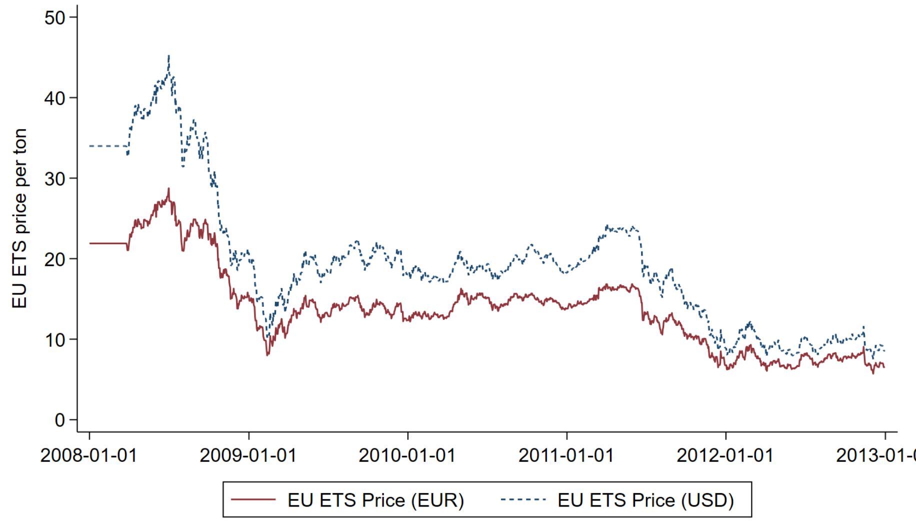


Figure 1: EU ETS Price over Phase II

industrial plants across a wide range of industries that generate heat, steam, or power on site. Additional industrial installations are included because they specialize in carbon-intensive processes and exceed specific capacity thresholds. Process-based definitions target pulp and paper mills, coke ovens, petroleum refineries, non-metallic mineral products (including the manufacture of glass, ceramics, and cement), and the manufacture of basic metals. Beginning in 2012, emissions from other industries, such as aviation, have been included in the EU ETS as well. Indirect emissions (emissions from sources that are not owned and not directly controlled by the firm), are not taken into account, nor are electricity imports.

Specifically, at the end of each year, plants regulated under the EU ETS are required to surrender one European Union Allowance (EUA) for each ton of CO_2 equivalent they have emitted over the year. They may buy additional EUAs or sell excess EUAs at a uniform price. Within limits, EUAs can be banked or borrowed to balance needs across years and, since 2008, across trading phases. The total amount of EUAs in the system is limited and linearly declines over time. Trading indicates the scarcity of EUAs, resulting in a positive price in the permit market.

Figure 1 plots the price of EUA December futures contracts, the primary trading instrument in the EU ETS (Ellerman et al., 2016). Due to our research interest, we mainly focus on Phase II. As Phase II began, the price reached almost 30 euros before it fell again by about 50 percent as a result of the economic crisis of late 2008. After a partial recovery in early 2009, the price stabilized at around 15 euros for two years, until summer 2011, when it fell another 50% to a new low of 7–8 euros in 2012. The price further declined to around 4 euros as Phase III began. Despite predictions by some observers that the price would again fall to zero, it did not, with 3.65 euros being the lowest price observed.

We focus on Phase II for two key reasons related to Phase I's limitations, and we further exclude Phase

III due to overlapping policy influences, as explained below. We exclude Phase I primarily for two reasons. First, Phase I operated as a pilot phase that focused on establishing the institutional infrastructure of the EU ETS, resulting in inconsistent caps and volatile carbon prices. In this stage, allowances were freely allocated based on historical emissions, and the overall cap was relatively loose. Although allowance prices initially appeared reasonable, they later experienced extreme volatility—rising above 30 euros at their peak and collapsing to near zero, as a result of poor allocation and lack of market expectations. Second, Phase I lacked the banking mechanism critical for price stability: Surplus allowances could not be carried over to Phase II, whereas Phase II allowances could be banked for use in Phase III and beyond (when a tighter cap and higher prices were anticipated). This meant that as Phase I emissions became clear to be below the cap, the price of EUA in Phase I plummeted to just a few euro cents, leaving little price variation to identify effects.

We also exclude Phase III, primarily due to concerns about overlapping energy and climate policies. Since 2012, other globally influential ETS programs have emerged. For example, at the beginning of 2013, California in the U.S. became the first and only state to put a comprehensive mandatory carbon regulation in place in the form of a cap-and-trade system that applies universally to all industrial GHG emissions (Bartram et al., 2022). At the same time, China's National Development and Reform Commission (NDRC) approved pilot emissions trading schemes in regions including Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, Shenzhen, and Fujian, which were gradually launched between 2013 and 2014. These overlapping policies complicate efforts to isolate the specific effect of EU ETS.

Therefore, our analysis focuses on Phase II (2008–2012). A potential concern is confounding economic fluctuations during this period, specifically the Great Recession, which may have independently affected exports. To address this, we control for recession-related factors and test the robustness of our findings to these controls, as discussed in Section 4.2, where the results remain consistent even after accounting for differential exposure to the Great Recession.

2.2 Data

We utilize two firm-level datasets and the EU ETS price dataset to construct main variables. The first dataset is the China Customs Dataset (2005–2012), which provides export and import values at the firm-product-country-year level for all exporters and importers in China. We define a product using the Harmonized System (HS) 4-digit code and focus on firms' export volume, export quantity, and export prices of EU ETS-regulated products from 2008 to 2012 as our main dependent variables. In addition, we use firm-level export data from 2005 to 2007 as baseline weights and construct time-varying, firm-level measures of the EU ETS price exposure by incorporating EU ETS price data.[3]

Second, to measure firm-level characteristics such as total factor productivity (TFP) and financial constraint indicators, we merge the China Customs Dataset (2008–2012) with China's State Administration of Taxation (SAT 2008–2012) using firm names. The SAT is the counterpart of the IRS in China and is in charge of tax collection and auditing, which includes information on firms' total output, value-added, employment, net asset value, cash flow statements, and other fundamental financial indicators.

Finally, we collect daily price of EUA December future constracts manually and fill in missing values for non-trading days with the nearest available price from the previous or following weekday. We then compute the annual average of the daily price and use it to construct EU ETS shock measurements via both import and export linkages.

Since EU ETS only applies to specific industries, we further restrict the sample to firms trading (exporting or importing) with the EU market in these regulated industries. Approximately 20% of the matched firms operate within the relevant product scope, but only half of them engage in actual trade (export or import) with the EU. Consequently, we retain 27,793 firms and construct an unbalanced panel with 564,786 transaction observations at the year-destination-HS4-firm level, covering all affected products in our baseline regression.[4] This matched sample enables us to simultaneously investigate exporters' performance, the transmission of EU ETS shocks via international trade linkages, and firm-level heterogeneity in impacts. To examine the spillover effects in more detail, we calculate each firm's export ratio to the EU market for regulated products, as well as its market share in the export market for those products, enabling a more precise empirical specification.

Crucially, the merged dataset preserves overall export patterns and doesn't have concerns about sample selection bias. Table A1 reports summary statistics of key variables, comparing the matched dataset with the original customs data. We restrict the sample to observations of affected products exported to the EU to be consistent with our baseline regressions. The results indicate that the matching procedure does not introduce systematic differences.

2.3 Stylized Facts

Figure 2 illustrates the aggregate export ratio of regulated products to EU markets and the EU ETS price over the specified period. The black solid line shows the aggregate export ratio of regulated products to EU markets, while the maroon long-dash and navy short-dash lines show the EU ETS price per ton

[3] We first use each firm's export share to each country and product in 2007. If a firm had no export or import transactions in 2007, we trace back year by year to 2006 and 2005.

[4] For comparison, if we consider all the export firms instead of the firms exporting affected products to the EU, we can get 293,922 firm-level matches from the SAT dataset (2008–2012), drawn from a broader pool of 540,662 firms recorded in the China Customs Dataset.

in euros or US dollars, respectively. The global financial crisis of 2008 led to a relative abundance of European firms' carbon quotas, resulting in the EU ETS price dropping sharply in 2009, after which it declined over time, which is consistent with our description in figure 1. Meanwhile, the overall export ratio of regulated products to EU markets decreased during these years, demonstrating that fluctuations in the EU ETS price may influence the product-country structure of Chinese exports through international trade networks.

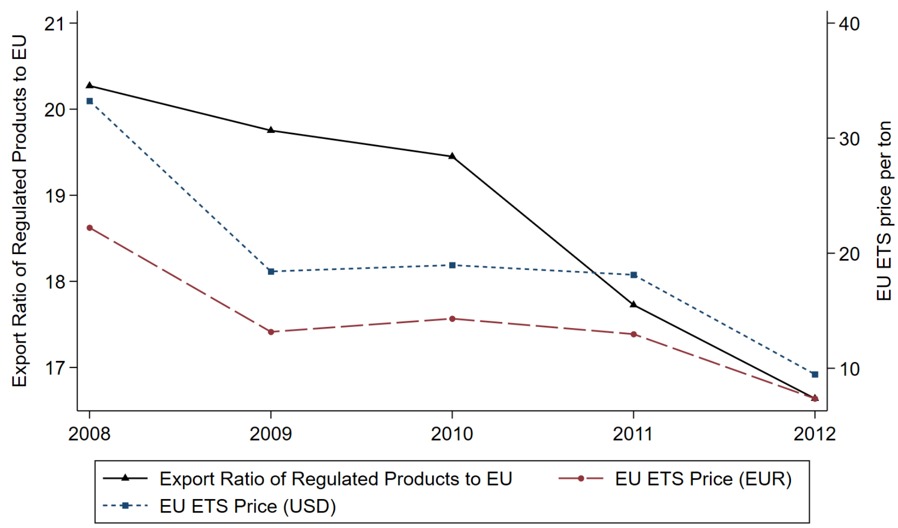


Figure 2: Export Ratio of Regulated Products to EU Markets and EU ETS Prices over Phase II

The stylized facts in figure 2 suggest that the EU ETS may affect the export behavior of Chinese firms. They also inform our model specification and the analysis of firm heterogeneity, guiding the subsequent empirical framework. The decline in the overall export ratio reflects a weighted average of firm-level declines in exports of regulated products to the EU. However, firms' heterogeneous responses not only alter their own export share of regulated products to EU markets but also shift their export composition relative to other products or markets. Accordingly, changes in the export share can be decomposed into three components: (1) the within-firm effect, defined as changes in a firm's share of exports to the EU in regulated goods relative to its own prior period; (2) the between-firm effect, capturing differences in export shares across firms relative to the current period's average across all firms; and (3) the entry-exit effect.

Taking it formally, for a certain firm i in year t, denote its export value of regulated goods to EU markets by $\text{Export}_{\text{EU\_regulated},it}$ and its overall export value of regulated goods by $\text{Export}_{\text{regulated},it}$, then firm i's market share of the regulated goods at time t is:

$$\omega_{it} = \frac{\text{Export}_{\text{regulated},it}}{\sum_i \text{Export}_{\text{regulated},it}},$$

and firm i's export ratio to the EU market among all its regulated products at time t is:

$$\mathrm{ES}_{it} = \frac{\mathrm{Export}_{\mathrm{EU\_regulated},it}}{\mathrm{Export}_{\mathrm{regulated},it}}.$$

Therefore, the aggregate export ratio of regulated products to EU markets ES_t can also be written as a weighted average of firms' regulated products' EU export ratio ES_{it}, weighted by their share in these markets ω_{it}: [5]

$$\mathrm{ES}_t = \frac{\sum_i \mathrm{Export}_{\mathrm{EU\_regulated},it}}{\sum_i \mathrm{Export}_{\mathrm{regulated},it}} = \sum_i \frac{\mathrm{Export}_{\mathrm{regulated},it}}{\sum_i \mathrm{Export}_{\mathrm{regulated},it}} \cdot \frac{\mathrm{Export}_{\mathrm{EU\_regulated},it}}{\mathrm{Export}_{\mathrm{regulated},it}} = \sum_i \omega_{it} \mathrm{ES}_{it}. \quad [1]$$

The year-to-year change in the aggregate export share of regulated products to the EU can be decomposed into three parts: the within-firm adjustments in export ratio, between-firm heterogeneity in responses to the EU ETS, and the the entry-exit effect:

$$\begin{aligned}\Delta \mathrm{ES}_t = & \sum_{i \in S} \omega_{it-1} \left(\mathrm{ES}_{it} - \mathrm{ES}_{it-1}\right) \\ & + \sum_{i \in S} \left(\omega_{it} - \omega_{it-1}\right)\left(\mathrm{ES}_{it-1} - \mathrm{ES}_{t-1}\right) + \sum_{i \in S} \left(\omega_{it} - \omega_{it-1}\right)\left(\mathrm{ES}_{it} - \mathrm{ES}_{it-1}\right) \\ & + \sum_{i \in entry} \omega_{it} \left(\mathrm{ES}_{it} - \mathrm{ES}_{t-1}\right) \\ & - \sum_{i \in exit} \omega_{it-1} \left(\mathrm{ES}_{it-1} - \mathrm{ES}_{t-1}\right), \end{aligned} \quad [2]$$

where ES_{t-1} denotes the aggregate export ratio in regulated products to the EU market in the previous year, referred to as the reference export share level.

We now elaborate on each term in equation [2] as follows. The first term of equation [2] is the within-firm effect, the second and third terms are the between-firm (reallocation) component while the last two terms are the contribution of entry and exit, respectively. Equation [2] states that the aggregate export ratio in regulated products to EU market can decrease for several reasons. A negative within-firm effect means that surviving exporters experience a decrease in their own export ratio. A negative between-firm effect means that export is reallocated towards low-export ratio (in regulated products to EU market) survivors so that these exporting firms become larger. The contribution of entrants and exiters is allowed to be positive or negative. This depends on whether their export ratio is higher than the reference export

[5] The main pattern remains robust when we use each firm i's total exports in year t as the denominator. In this alternative aggregation, the resulting ratio captures two concurrent effects: changes in export destinations and changes in product scope. Figure A1 illustrates this robustness.

ratio level.

Figure 3 shows the accumulated effect (using year 2008 as the benchmark year) during the 2008-2012 period. The black solid line illustrates the within-firm effect, the maroon long-dash line illustrates the between-firm effect, while the teal short-dash line shows the entry-exit effect. Several patterns should be paid attention to. First of all, the exit-entry effect is close to zero in almost all years, suggesting that the adjustments of EU export stem mainly from the intensive margin instead of extensive. In addition, the within-firm effect and the between-firm effect show a slightly opposite trend, with firms lowering their export ratio of the regulated products to EU market as the EU ETS price decreased, while the positive between-firm effect doubts the existence of the reallocation towards low-export ratio survivors.

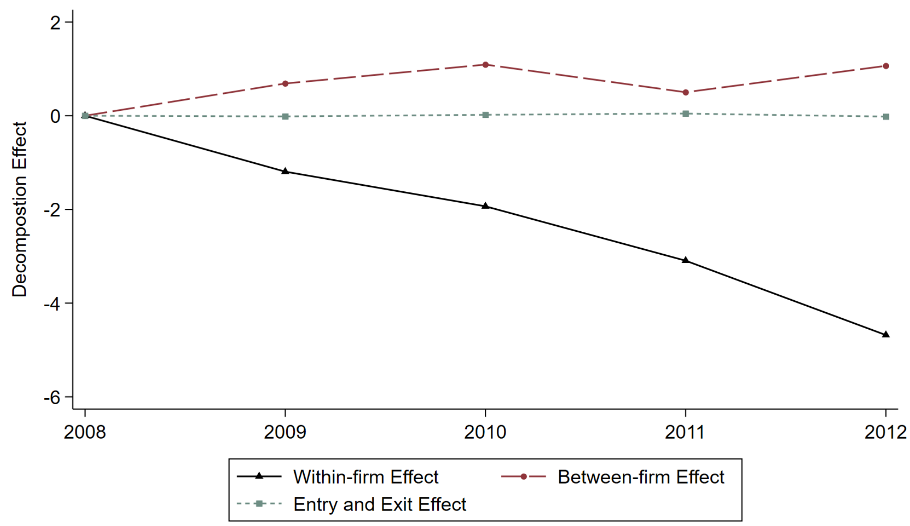
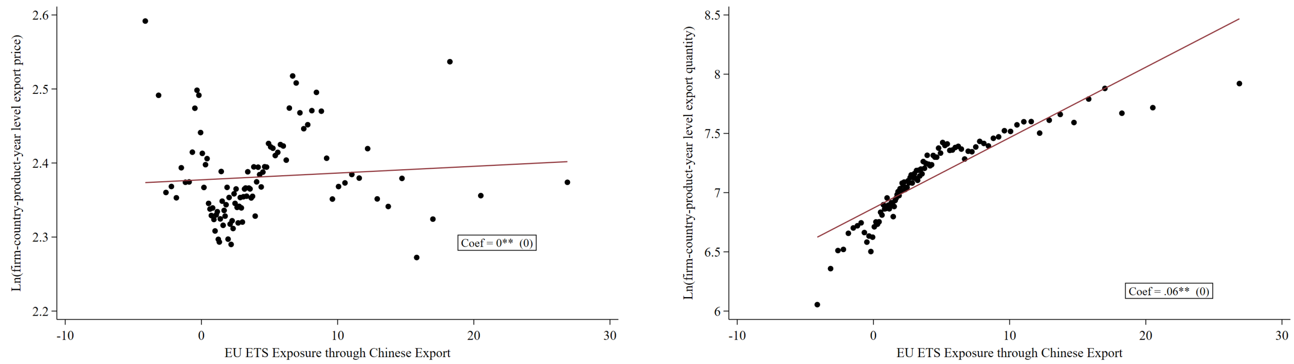


Figure 3: Decomposition of the Export Ratio over Phase II

Figures 2 and 3 reveal a positive correlation between the export share and EU ETS price at the aggregate level. To explore how EU ETS prices affect firm behavior in greater detail, we use firm-level bin-scatter plots to compare each firm's export behavior with its firm-specific exposure to EU ETS price shocks (see Section 2.4.1 for details on how this exposure is constructed). Because export value is the product of export price and quantity, we examine the relationship between our constructed shock and both export price and quantity. Figure 4 presents bin-scatter diagrams of firms' export price and quantity against their EU ETS shock. The results indicate a statistically and economically significant positive relationship between export quantity and the EU ETS shock, while the relationship between export price and the shock is economically negligible.



(a) Export Price

(b) Export Quantity

Figure 4: Bin-scatter Plots of Firms' Export Outcomes under EU ETS Exposure

Notes: These scatter plots show the relationship between firm-level EU ETS shocks and (a) export price and (b) export quantities. We control product fixed effect, destination fixed effect and year fixed effect to absorb all the potential differences in export outcomes related to the specific industry, destination and year. We split the range of x-variable into 100 equal-sized bins (based on quantiles) and each dot show the average x and y values within each bin. Fitted lines come from binned scatter plots controlling for the following fixed effect.

In conclusion, the stylized facts above indicate that the export value is positively related to the EU ETS price, and the micro heterogeneity from firms' response to the shock cannot be ignored. Furthermore, the EU ETS shock mainly affects the export value through export quantity rather than export price. Such phenomena motivate our empirical specification in section 3.1, and more quantitative assessment in section 5 discussed below.

2.4 Variable and Summary Statistics

2.4.1 EU ETS Price Exposure Measures

To capture firms' exposure to EU ETS price fluctuations, we employ a shift-share approach (Bartik, 1991; Topalova and Khandelwal, 2011; Goldsmith-Pinkham et al., 2020), using firms' historical export structure as the weights and calculating the weighted average of the EU ETS price for each firm in a given year.

The baseline period for constructing the shift-share instrument varies with each firm's export history. For instance, firms with export records in 2007 use year 2007 as the baseline, with shift-share weights derived from their HS 6-digit product export distribution that year. For firms without export records in 2007 but in 2006, the 2006 export distribution serves as the basis. More generally, the baseline period is selected from the years 2005 to 2007. This approach ensures that our measure of EU ETS price exposure reflects pre-existing trade patterns rather than contemporaneous firm-level adjustments. The measure is calculated as follows:

$$\text{ETS\_Shock}_{it}^{\text{export}} = \sum_{n \in N_{i0}^{E}} \sum_{\omega \in \Omega_{i0}^{E}} \frac{X_{in\omega 0}}{\sum_{m \in N_{i0}^{E}} \sum_{s \in \Omega_{i0}^{E}} X_{ims0}} \cdot \text{price}_{n\omega t},$$

where $\text{price}_{n\omega t}$ denotes the EU ETS price in year t for product ω originating from country n, which is zero if n is not a member of the EU ETS or if product ω is not covered by the EU ETS. N_{i0}^{E} and Ω_{i0}^{E} are sets collecting company i's export countries and export product categories in the base period. This export-related EU ETS shock is computed as a weighted sum of EU ETS prices across all origin countries and products in a firm's historical export portfolio. The weights correspond to the firm's export shares in the baseline period, placing greater emphasis on products and destinations that historically accounted for a larger proportion of the firm's trade. This firm-level measure enables us to assess how EU ETS price fluctuations affect firms through international trade linkages, thereby shaping their export performance and broader economic outcomes.

2.4.2 Control Variables

We include two control variables. First, we follow the same method and account for the EU ETS shocks transmitted through the import network by constructing a weighted average measure at the firm-year level ($\text{ETS\_Shock}^{\text{import}}$), capturing the indirect impact of carbon pricing via global supply chains. Second, we include the logarithm of the firm-level total factor productivity (TFP) estimates ($Ln(TFP\_acf)$), which are derived using structural production function estimation techniques. Following Olley and Pakes (1996), Levinsohn and Petrin (2003) and Ackerberg et al. (2015), we primarily employ the ACF method (Ackerberg et al., 2015) to estimate TFP, ensuring a robust control for firm-specific productivity dynamics.

2.4.3 Summary Statistics

Table 1 provides an overview of the key variables used in our empirical analysis. Panel A presents descriptive statistics at the firm-destination-HS4-year level. The primary dependent variables include the logarithm of firm export value ($Ln(value)$), export quantity ($Ln(quantity)$), and export price ($Ln(price)$). Additionally, the table reports the exposure to the EU ETS shock through export and import linkages, denoted as $\text{ETS\_Shock}^{\text{export}}$ and $\text{ETS\_Shock}^{\text{import}}$, respectively. These variables capture the extent to which firms are affected by carbon pricing policies in their trade relationships. After that, we show a series of variables to account for firm heterogeneity. First, we report the logarithm of total factor productivity ($Ln(TFP\_acf)$), which falls within the expected range for this indicator during the sample period. Furthermore, we examine firms' financial constraint based on the ratio of cash holdings to total assets (Constraint_Dummy(cash ratio)). Finally, we focus on the firms' scale and create a dummy based on the 75th percentile of the corresponding industry's net income distribution in the base period (Size_Dummy(income)).

Panel B shifts the focus to firm-level aggregation, which will be used in the subsequent firm-level regressions. The variable ES_{it} measures the ratio of firms' exports in regulated product categories destined for the EU market. On average, 34.2% of a firm's exports are from regulated products to the EU market, but this share exhibits substantial variation, ranging from 0 to 100%. This suggests that while some firms are highly specialized in exporting to the EU, others have more diversified export portfolios. Furthermore, the variable ω_{it} captures the firm's market share in the regulated product categories. The mean market share is relatively low at 0.02%, indicating that most firms hold only a marginal position in the market. However, the maximum value of 3.07% suggests the presence of some relatively large exporters, which supports the plausibility of assuming monopolistic competition.

Overall, the summary statistics highlight the substantial heterogeneity in firms' exposure to EU carbon policies and market positioning. This variation provides the foundation for our empirical analysis, allowing us to investigate how firms with different characteristics respond to policy shocks and market dynamics.

Table 1: Descriptive Statistics of Key Variables

	Summary statistics				
Variable	Obs.	Mean	Std. Dev.[a]	Min	Max
Panel A: Firm–destination–HS4–year level					
Ln(value)	564,786	9.517	(2.716)	0	21.872
Ln(quantity)	561,158	7.151	(3.374)	0	21.756
Ln(price)	561,158	2.404	(2.381)	−7.611	17.476
$\text{ETS\_Shock}^{\text{export}}$	564,786	4.292	(5.338)	0	35.558
$\text{ETS\_Shock}^{\text{import}}$	564,786	1.449	(4.022)	0	33.238
Ln(TFP_acf)	564,786	1.459	(0.997)	−5.188	7.986
Constraint_Dummy (cash ratio)	564,786	0.298	(0.458)	0	1
Size_Dummy (income)	564,786	0.270	(0.444)	0	1
Panel B: Firm–year level					
ES_{it}	65,250	34.228	(34.045)	0	100
ω_{it}	65,250	0.020	(0.027)	0	3.066

Notes: Panel A summarises variables at the firm-destination-HS4-year level, restricted to EU-regulated products (564,786 observations from 27,793 firms). Panel B reports firm–year level statistics for variables used in further discussion (65,250 observations). All monetary values are in current USD; logarithms are natural logs. Standard deviations are reported in parentheses.

3 Empirical methodology

3.1 Empirical Specification

We use the following high-dimensional fixed effect regressions to evaluate the impact of EU ETS:

$$Y_{icjt} = \alpha + \beta \cdot \text{ETS\_Shock}_{it}^{\text{export}} + \gamma' X_{it} + \lambda_i + \mu_{ct} + \mu_{jt} + \epsilon_{icjt}, \quad [3]$$

where Y_{icjt} indicates different dependent variables of firm i with export destination-HS4 industry cell "$c-j$" in year t. We mainly focus on the logarithm of (regulated products') export value, export price, as well as export quantity in the benchmark regression. $\text{ETS\_Shock}_{it}^{\text{export}}$ is the weighted averaged EU ETS shocks transmitted by the export network of firm i in year t, which is the core independent variable we are interested in. The control variables, X_{it}, include the weighted averaged EU ETS shocks transmitted by import network of firm i in year t and the logarithm of the estimated total factor productivity (TFP) of firm i in year t (Ackerberg et al., 2015). λ_i is the firm fixed effect, while μ_{ct} controls the specific destination-year fixed effect and μ_{jt} controls the HS4 industry-year fixed effect, respectively, thus different industry/destination country trading policies during each year can be controlled. ϵ_{icjt} is the error term, which is allowed to be correlated within different destination countries, industries or years. The parameter β captures the effect of the EU ETS shock on Chinese firms' exports to the EU. A positive β indicates that a reduction in the stringency of the EU ETS is associated with a decline in exports from China to the EU, which aligns with the stylized facts.

We also control for a more restrictive fixed effect, in which we control for the "destination-HS4 industry-year" triple time fixed effect:

$$Y_{icjt} = \alpha + \beta \cdot \text{ETS\_Shock}_{i,t}^{\text{export}} + \gamma' X_{it} + \lambda_i + \mu_{cjt} + \epsilon_{icjt}, \quad [4]$$

where other variables are the same as equation [3].

Motivated by the decomposition stylized facts, we further investigate which types of firms primarily drive the within-firm effect. This naturally links to the firm heterogeneity issue. We therefore examine a set of firm-level characteristics that may shape Chinese exporters' responses to the EU ETS price shock, including financial constraints, producticiy levels, and firm sizes. The modified regression for the heterogeneous discussion is defined as follows:

$$Y_{icjt} = \alpha + \beta_1 \cdot \text{ETS\_Shock}_{it}^{\text{export}} + \beta_2 \cdot \text{ETS\_Shock}_{it}^{\text{export}} \cdot \text{Factor}_{i0} + \gamma' X_{it} + \lambda_i + \mu_{ct} + \eta_{jt} + \epsilon_{icjt}, \quad [5]$$

where Factor_{i0} denotes alternative measures of various factors in the baseline period, with all other variables remaining consistent with those in equation [3].[6]

3.2 Back-of-the-Envelope Analysis

Alongside the empirical patterns identified, a natural question arises: to what extent does the EU ETS price shock contribute to the decline in exports of regulated products to the EU, relative to the exports of regulated products to other countries and districts? To what extent the exact level of fluctuations of EU ETS price affect the firms' within-firm effect and between-firm effect? Using the coefficients estimated from specification [3] or [4] above, we can answer these questions and quantify this contribution through a back-of-the-envelope analysis, which we refer to as the "ripple effect."

Take the export value in the benchmark regression [3] as a naive example. Since we can observe the actual export for a certain firm–destination country-HS4 industry-year cell, denoted as: $\text{Exports}_{icjt,\text{actual}}$, we can calculate the counterfactual exports without EU ETS price shock as

$$\widehat{\text{Exports}}_{icjt,\text{counterfactual}} = \text{Exports}_{icjt,\text{actual}} \cdot \exp\left\{\widehat{\beta} \cdot \left(\text{ETS\_Shock}_{it}^{\text{counter}} - \text{ETS\_Shock}_{it}^{\text{export}}\right)\right\},$$

where $\text{ETS\_Shock}_{it}^{\text{counter}}$ depends on different counterfactual scenarios:

- If we assume that there is no environmental regulation in EU market, then $\text{ETS\_Shock}_{i,t}^{\text{counter}} = 0$ uniformly for all firm i in year t.
- If we assume that the EU ETS price shock is not that severe, then

  $$\text{ETS\_Shock}_{it}^{\text{counter}} = \min_t \text{ETS\_Shock}_{it}^{\text{export}}$$

  for all firm i in year t.
- If we assume that the EU ETS price shock is quite severe, then

  $$\text{ETS\_Shock}_{it}^{\text{counter}} = \max_t \text{ETS\_Shock}_{it}^{\text{export}}$$

  for all firm i in year t.

Given the above three situations and combined with the actual export circumstance, we can calculate the contribution of EU ETS price shock:

$$\text{Contribution}_t = \frac{\sum_{icj} \widehat{\text{Exports}}_{icjt,\text{counterfactual}} - \sum_{icj} \text{Exports}_{icjt,\text{actual}}}{\sum_{icj} \text{Exports}_{icjt,\text{actual}}}.$$

[6] We also consider a more restrictive time fixed effect for robustness.

We can also re-do the decomposition in section 2.3 to further discuss the change of export ratio.

4 Empirical results

This section reports the empirical findings on the spillover effects of the EU ETS. We begin by presenting the baseline specification results and the corresponding robustness checks. Next, we demonstrate that firms' heterogeneity stems primarily from their financial constraints, productivity levels, firm sizes, and discuss how these factors shape firms' adjustments to EU ETS price fluctuations. Finally, we further focus on within-firm effects and between-firm effects to highlight the main drivers of our findings.

4.1 Baseline Results

In Section 2.3, we decompose the overall variation of export outcomes into three components: within-firm effects, between-firm reallocation, and entry-exit dynamics. The decomposition reveals that entry and exit play a negligible role, while within-firm adjustments overwhelmingly drive the aggregate trends. In light of this finding, we focus our empirical analysis at the firm-destination-HS4-year level, starting with regressions on the intensive margin. Subsequent decompositions further reinforce this focus and suggest meaningful heterogeneity among firms.

Table 2 presents our baseline estimates. A clear pattern emerges: a decline in the EU ETS price leads to a reduction in export values of regulated products to the EU. This effect is primarily driven by changes in export quantities rather than prices, suggesting that shifts in market shares - likely due to intensified competition in the EU market - are the main transmission mechanism. Quantitatively, a one-unit decrease in the firm-level EU ETS shock reduces export value and quantity to the EU market by 2.1% and 1.9%, respectively. Over the sample period, the mean of independent variable fell from 5.01 in 2008 to 1.39 in 2012, implying an average decline of approximately 7.6% in export value.

In contrast, the coefficient on export prices is economically small and statistically insignificant, suggesting a limited pass-through of the EU ETS price to unit export prices. This finding supports the view that export prices are relatively rigid in the short run, particularly in the absence of substantial technological upgrading. Furthermore, this result aligns with the predictions of our general equilibrium model, in which EU ETS price fluctuations affect the aggregate price index of the EU but do not directly affect the export prices of other countries. These shocks alter competitive conditions in the EU market, prompting firms from other countries to adjust their export strategies accordingly.

Table 2: How the EU ETS Carbon Price Affects Chinese Firms' Exports

DEP. VAR.	Ln(value)		Ln(price)		Ln(quantity)	
	(1)	(2)	(3)	(4)	(5)	(6)
ETS_Shock^{export}	0.021***	0.021***	0.002	0.002	0.019***	0.019***
	(0.003)	(0.003)	(0.002)	(0.002)	(0.003)	(0.003)
ETS_Shock^{import}	-0.002	-0.001	-0.004**	-0.004*	0.003	0.003
	(0.004)	(0.004)	(0.002)	(0.002)	(0.004)	(0.004)
Ln(TFP_acf)	0.002	0.002	0.012	0.011	-0.007	-0.007
	(0.010)	(0.010)	(0.008)	(0.008)	(0.012)	(0.012)
Observations	559 619	554 361	555 983	550 734	555 983	555 983
R^2	0.356	0.387	0.678	0.693	0.498	0.498
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
HS4–Year FE	Yes	No	Yes	No	Yes	No
Destination–Year FE	Yes	No	Yes	No	Yes	No
HS4–Destination–Year FE	No	Yes	No	Yes	No	Yes

Notes: The dependent variable is logarithmic term of export value, export price and export quantity in the firm-HS4-destination-year level. The main independent variable is ETS_Shock^{export}. Standard errors are shown in parentheses. Statistical significance is indicated as: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

4.2 Robustness Checks

To verify the reliability and validity of our baseline findings, we perform five sets of robustness checks as detailed below.

4.2.1 Examination of the Impacts of EU ETS's First Stage

As outlined in the institutional background, Phase I of the EU ETS saw minimal price fluctuations and a relatively small number of regulated firms. For this reason, we focus our baseline analysis on Phase II. However, a potential concern is that firms' export structures may have been altered due to policies implemented during Phase I, which could compromise the exogeneity of the shift-share approach. To address this issue, we identified industries that emerged only after 2008 and used this subsample to re-estimate our baseline results. Table A2 indicates that the estimates remain consistent both economically and statistically, demonstrating the robustness of our findings.

4.2.2 Assessment of the Exogeneity of EU ETS Price

Given China's status as a major trading nation, a potential concern in using Chinese firms as our sample to study the spillover effects of the EU ETS is that China's exports could influence EU ETS prices in the European market—possibly through channels such as firms sourcing high-carbon inputs from China or relocating certain production processes to China. To address this issue, we regress EU ETS price on EU's import volumes (total imports in the regulated products and unregulated products), using contemporaneous values and one- and two-year lags. Table A3 indicates that the total import value does not exert a significant effect on EU ETS prices. Moreover, the estimated coefficients for the imports of affected products and unregulated products are nearly identical. These results are consistent with Colmer et al. (2024), indicating that there is no significant spillover effect through imports of high-carbon inputs and alleviating concerns about the exogeneity of EU ETS prices.

4.2.3 Excluding the Impact of Exchange Rate

In the baseline regression, we employ the EU ETS price denominated in US dollars, since the majority of transactions by Chinese firms are invoiced in US dollars. However, this specification may conflate exchange rate effects with estimated impacts. To verify that our results are not confounded by exchange rate fluctuations, we reconstruct the independent variables using the EU ETS price denominated in euros and re-estimate the baseline model. The results reported in Table A4 remain consistent under this alternative specification.

4.2.4 Excluding the Impact of the Global Financial Crisis

Our sample period, 2008–2012, encompasses the global financial crisis, which may influence our estimates through two primary channels. First, if the financial crisis significantly contributed to the decline in EU ETS price and reduced import demand within the EU market, this could introduce omitted-variable bias into our estimations, confounding the true effect of EU ETS shocks with crisis-induced demand changes. Second, firms more severely affected by the financial crisis might adjust their export strategies, potentially increasing exports to the EU market instead of the United States, leading to an underestimation of our results.

To address these concerns, we introduced two dummy variables. One indicates the financial crisis period (assigned a value of 1 for the years 2008–2009) and another identifies firms that exported regulated goods to the US before the crisis. We then interacted these variables with our main independent variable. If the first concern is predominant, the estimated coefficient for the interaction term would be significant, while the coefficient for the EU ETS price shock would be insignificant. If the second concern holds, firms with pre-crisis US export activities might exhibit a smaller decrease compared to others.

Table A5 presents our estimation results under these scenarios, leading to two key findings. First, the spillover effect remains consistent before and after the financial crisis. However, there is a tendency for a more pronounced response during the 2008–2009 period, possibly because firms sought to protect profits through price adjustments amid significant demand reductions. Post-crisis, as demand gradually recovered, the response diminished, with no significant price changes observed. Second, firms which exported to the US market prior to the financial crisis adjusted more significantly; yet, even when excluding these firms, the estimated coefficient remains significantly positive. If the financial crisis had prompted some firms to shift exports from the US to the EU market, these firms would likely have been less responsive to EU ETS price changes. However, our results indicate a larger response, suggesting that the financial crisis did not affect our estimation through a global supply-side adjustment.

4.2.5 Product Reclassification at the HS 2-Digit Level

We manually matched the implementation scope of the EU ETS to the HS 2-digit level, whereas our baseline regression is conducted at the HS 4-digit level to retain more precise transaction-level variation. This may raise concerns about inconsistent specification. To test the robustness of our main results, we re-estimated our model using HS 2-digit product classifications. The results in Table A6 are still significant, and the magnitude is larger than the baseline results. Because aggregation from HS 4-digit to 2-digit increases the total export value, it is reasonable to have a relatively larger estimated coefficient.

4.3 Firm Heterogeneity

After confirming the existence of the spillover effect, we further explore which firms adjusted their export values more significantly in response to changes in EU ETS prices.

Since fluctuations in EU ETS prices only directly affect local producers' costs without altering the production and export behavior of these foreign firms, we hypothesize that the primary transmission mechanism for Chinese exporters operates through changes in competition dynamics within the EU market. This hypothesis will be further examined in Section 6. Consequently, firm characteristics related to competitiveness are expected to influence the magnitude of the spillover effect.

Existing literature has demonstrated that firms' production and export behaviors are largely restricted by the firms' financial situation (Manova et al., 2015; Feenstra et al., 2014; Manova, 2013; Amiti and Weinstein, 2011; Fan et al., 2015), scale(Guariglia and Mateut, 2010) and productivity (Chaney, 2008; Melitz, 2003; Crinò and Epifani, 2012). To examine the heterogeneous effects of these factors, we construct the measures as follows. First, following Kaplan and Zingales (1997); Whited and Wu (2006), we use cash-to-assets as a proxy for liquidity constraints due to data limitations in other dimensions. Firms with a cash-to-assets ratio below the industry-year median are considered more financially constrained, as they have fewer liquid resources to meet short-term obligations and rely more heavily on external financing. Second, we calculate firm-level productivity based on Ackerberg et al. (2015) to measure the competitiveness related to TFP. Finally, smaller firms often concentrate on a narrower range of products or destinations and exhibit lower flexibility in adjusting to shocks. They may also be more vulnerable to information asymmetry due to limited public disclosure, which increases their difficulty in securing external funding. Inspired by Guariglia and Mateut (2010); Bartram et al. (2022), we use operating revenue from a firm's main business as an additional measure, classifying firms as relatively small firms if their annual sales revenue is below the 75th percentile of the corresponding industry's distribution in the base period.

The results justify the significant difference in different kinds of firms. First, financially constrained firms exhibit smaller export adjustments. This finding underscores the need for firms to strengthen their financing capabilities and maintain sufficient liquidity to mitigate potential risks. Second, we find that firms with higher productivity levels respond more strongly to shocks, reinforcing the idea that enhancing productivity is a key strategy for mitigating the impact of external shocks. Finally, we focus on firms' size and find that smaller firms exhibit less flexible adjustments compared with the larger firms.

Table 3: Which Types of Firms Are More Susceptible to the Spillover Effect?

DEP. VAR. Ln(value)	(1)	(2)	(3)	(4)	(5)	(6)
	Constraint_Dummy (cash ratio)		*Ln*(TFP_acf)		Size_Dummy (income)	
ETS_Shock^{export}	0.025***	0.025***	0.016***	0.016***	0.026***	0.026***
	(0.004)	(0.004)	(0.003)	(0.003)	(0.004)	(0.004)
Constraint_Dummy × ETS_Shock^{export}	-0.010**	-0.011**				
	(0.005)	(0.005)				
Ln(TFP_acf) × ETS_Shock^{export}			0.005***	0.005***		
			(0.002)	(0.002)		
Size_Dummy × ETS_Shock^{export}					-0.008*	-0.009*
					(0.005)	(0.005)
Observations	559 619	554 361	559 619	554 361	559 619	554 361
R^2	0.356	0.387	0.356	0.387	0.356	0.387
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
HS4–Year FE	Yes	No	Yes	No	Yes	No
Destination–Year FE	Yes	No	Yes	No	Yes	No
HS4–Destination–Year FE	No	Yes	No	Yes	No	Yes

Notes: Sample at the firm–HS4–destination-year level. Constraint_Dummy is 1 if the firm was financially constrained in 2008 (cash-asset ratio). Robust standard errors in parentheses. Ln(TFP_acf) measures firm productivity. Size_Dummy is 1 if their annual sales revenue is below the 75th percentile of the corresponding industry-year distribution in 2008. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.4 Further Discussion: Within-firm and Between-firm Specifications

In Section 2.3, we decompose the overall EU export ratio for regulated products into three components: within-firm effect, between-firm effect, and entry and exit effects, following Equation 2. In the final part of Section 4, we followed Panon (2022) and applied first-differences specification to test the changes in within-firm effect and between-firm effect.

Within-firm effect refers to $\sum_{i \in S} \omega_{it-1} (\text{ES}_{it} - \text{ES}_{it-1})$, focusing on the change $\text{ES}_{it} - \text{ES}_{it-1}$ between different years. Thus, our within-firm specification is as follows:

$$\Delta \text{ES}_{it} = \text{ES}_{it} - \text{ES}_{it-1} = \beta_1 \Delta \text{ETS\_Shock}^{\text{export}} + \gamma' \Delta X_{it} + \Delta \eta_{jt} + \Delta \epsilon_{it} \quad [6]$$

The dependent variable is the difference of firm-level regulated products' export ratio to the EU market between periods $t-1$ and t. This first-difference approach controls for time-invariant unobserved factors influencing a firm's export structure that might correlate with EU ETS price levels. The presence of sector by year fixed effects $\Delta \eta_{jt}$ aims to control for sector-specific supply and demand shocks on both the EU and domestic market. This setup allows us to focus on the estimated coefficient β_1 to assess how fluctuations in EU ETS prices influence firms' EU export ratios over time.

The between-firm effect is defined as $\sum_{i \in S} (\omega_{it} - \omega_{it-1}) (\text{ES}_{it} - \text{ES}_{t-1})$, where our primary focus lies on the term $\omega_{it} - \omega_{it-1}$. Accordingly, our specification for the between-firm effect is as follows, with all other components remaining unchanged:

$$\Delta \omega_{it} = \omega_{it} - \omega_{it-1} = \beta_1 \Delta \text{ETS\_Shock}^{\text{export}} + \gamma' \Delta X_{i,t} + \Delta \eta_{jt} + \Delta \epsilon_{i,t} \quad [7]$$

Table 4 presents the results of these two specifications with varying control variables. Column (1) and (2) include controls for both the change in $\text{ETS\_Shock}^{\text{import}}$ and the change in $Ln(TFP\_acf)$, while Column (3) and (4) control only for the change in $\text{ETS\_Shock}^{\text{import}}$. The findings indicate that lower EU ETS prices significantly reduce firms' EU export ratios between periods $t-1$ and t. However, EU ETS price fluctuations do not have a statistically or economically significant impact on firms' market shares in the regulated products.

Table 4: Results of Within–Firm and Between–Firm Specifications

Dep.Var.	(1) *Within-Firm Effect* ΔES_{it}	(2) *Between-Firm Effect* $\Delta \omega_{it}$	(3) *Within-Firm Effect* ΔES_{it}	(4) *Between-Firm Effect* $\Delta \omega_{it}$
$\Delta\text{ETS\_Shock}^{\text{export}}$	0.597***	-0.000	0.557***	-0.000
	(0.063)	(0.000)	(0.040)	(0.000)
$\Delta\text{ETS\_Shock}^{\text{import}}$	-0.198**	0.000	-0.087*	0.000
	(0.083)	(0.000)	(0.052)	(0.000)
$\Delta Ln(TFP\_acf)$	-0.348	0.000***		
	(0.240)	(0.000)		
Observations	33 028	33 028	70 024	70 024
R^2	0.054	0.026	0.039	0.043
Industry–Year FE	Yes	Yes	Yes	Yes

Notes: The dependent variables are the change in EU export ratio (ΔES_{it}) and the change in market share of regulated products ($\Delta \omega_{it}$). Robust standard errors are in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5 Quantitative assessment

As discussed in Section 3.2, we can use the estimated coefficients to calculate the counterfactual export variables of interest, including the export values and ratios. We first evaluate both export values and export ratios under four different scenarios and then decompose the changes in export ratios using the estimated coefficients.

5.1 Export Ratio and Value

Figure 5 shows various aggregate export values under different EU ETS assumptions. The black solid line shows the actual export value in billion US dollars, while the maroon long-dash line shows the counterfactual export value without EU ETS export shock in billion US dollars. Furthermore, we also suppose two other circumstances: The teal short-dash line shows the counterfactual export value in billion US dollars if each firm faced its minimal EU ETS shock during Phase II, while the navy dash line shows the counterfactual export value in billion US dollars if each firm faced its maximal EU ETS shock during Phase II.

Several patterns align with our findings. Firstly, the counterfactual export values with EU ETS shock less than the actual shock are all no more than the actual export value (and vice versa), consistent with the positive relationship between firms' export value and its specific EU ETS shock. Secondly, since firms faced their most severe EU ETS shocks in 2008—and shocks eased during EU ETS Phase II—it is not surprising that the counterfactual export value under the maximal scenario matches the actual value in 2008, just as the minimal scenario aligns with the actual value in 2012. Finally, the impact of EU ETS shock is statistically significant, as has been discussed in Section 4, and economically significant as well. For example, comparing the maximal counterfactual shock with the actual shock, aggregate export values during Phase II were approximately 504.4 billion USD and 455.2 billion USD, respectively. This implies that if EU ETS prices had remained at their 2008 level, the high price would have stimulated Chinese firms to increase their total export value by 10.8% overall.

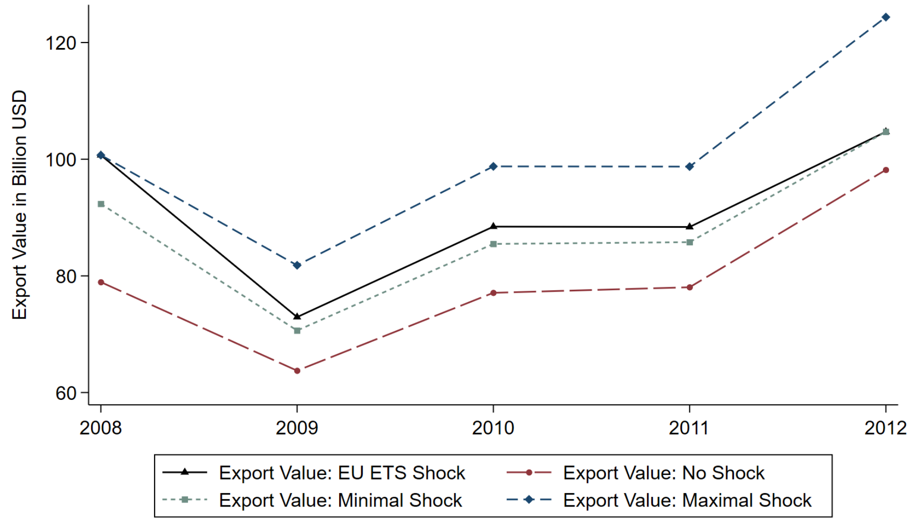


Figure 5: Export Value under different Shocks over Phase II

In contrast, Figure 6 presents aggregate export ratios (rather than values) under different EU ETS assumptions. The line patterns are exactly the same as those in Figure 5. Similarly, the counterfactual export ratio decreased compared with the actual export ratio when the counterfactual shock was less than the actual shock. These patterns, consistent with those in Figure 5, further reinforce the robustness of our empirical findings.

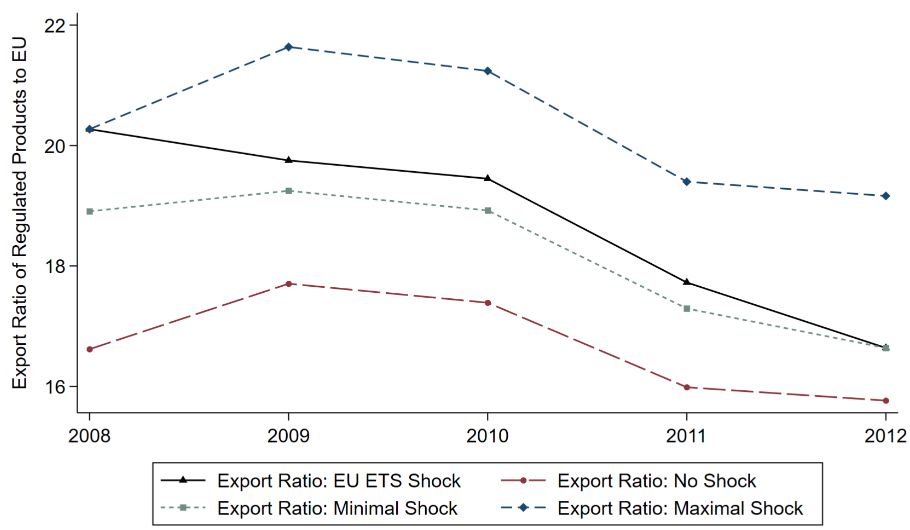


Figure 6: Export Ratio under different Shocks over Phase II

5.2 Decomposition

We also conducted the decomposition by constructing counterfactual export ratios using counterfactual export values. Figure 7 shows the actual and counterfactual accumulated within-firm effect, while Figure

8 shows the actual and counterfactual accumulated between-firm effect. The line patterns compared with the specific counterfactual shock situation are exactly the same as those in Figure 5 and Figure 6.

The differences between these accumulated effects offer valuable insights. Firstly, the magnitude of the within-firm effect exceeds that of the between-firm effect in most situations, indicating that firms' own adjustments in export ratios contribute more significantly to changes in the aggregate export share. Secondly, the within-firm effect by the actual EU ETS shock is the largest. Since the magnitude of the shock remain the same in each of the counterfactual EU ETS assumption, it is the variation rather than the scale of the shock that affects firms' own adjustment, indicating the importance of price uncertainty in firms' export behaviors. Thirdly, the within-firm and between-firm effects move in opposite directions, suggesting that even when overall exports decline, between-firm reallocations may provide a buffering effect. As the within-firm effect decreases, the between-firm effect remains mostly positive; consequently, the accumulated between-firm effect increases except in 2011. Fourthly, when the counterfactual shock is smaller than the actual shock, the between-firm effect remains nearly unchanged, whereas the within-firm effect decreases significantly. This once again supports the empirical patterns documented in Section 4. Finally, an interesting pattern emerges under the scenario of the most severe EU ETS price shock: Although the within-firm effect decreases only slightly, the between-firm effect increases substantially. This may indicate the presence of a Matthew effect, in which export values become increasingly concentrated among firms with larger export shares.

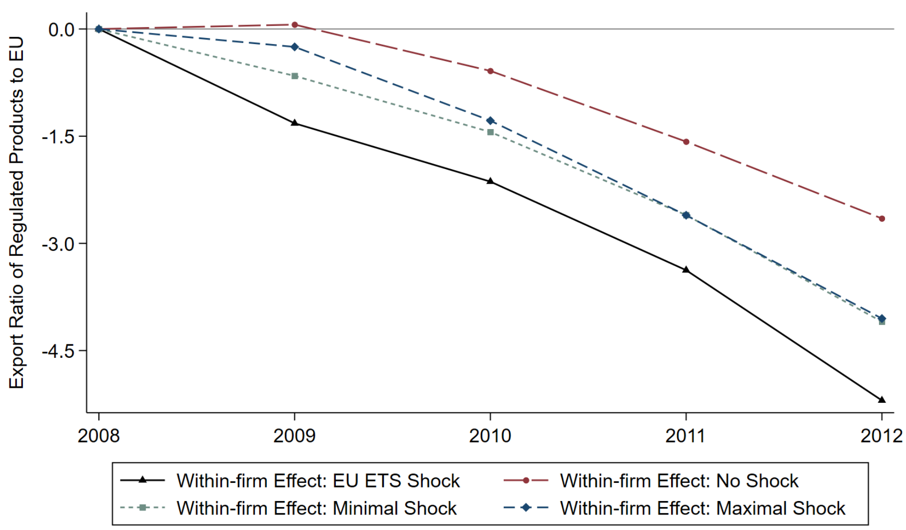


Figure 7: Within-firm Effect under different Shocks over Phase II

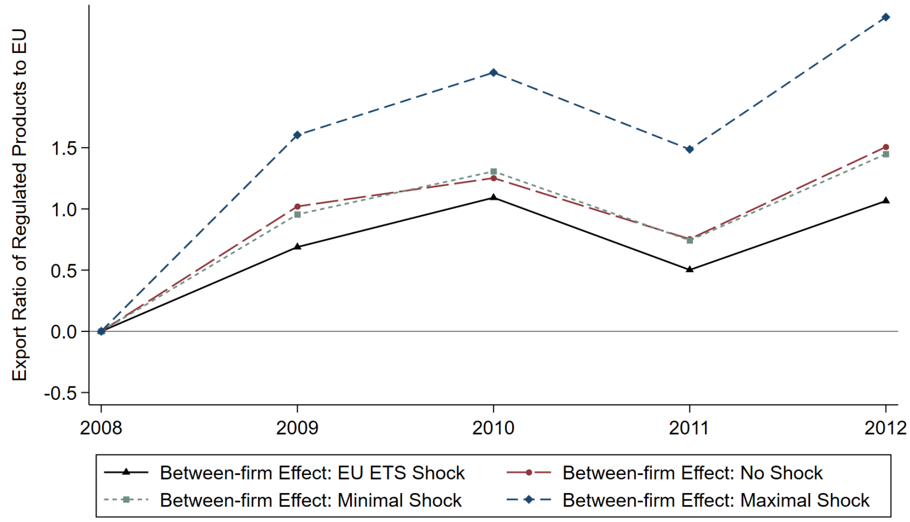


Figure 8: Between-firm Effect under different Shocks over Phase II

As discussed in Section 4.3, firm with financial constraints/with lower productivity level/with smaller size adjusted their export value less compared with those firms without financial constraints/with higher productivity level/with larger size. Figure 9 shows the further decomposition of the within-firm effect under different firm heterogeneity settings. Figure 9(a) and figure 9(b) categorize firms by their financial constraint status, using the cash-based indicator, while figure 9(c) and figure 9(d) are for the productivity level status and figure 9(e) and figure 9(f) are for the size status.

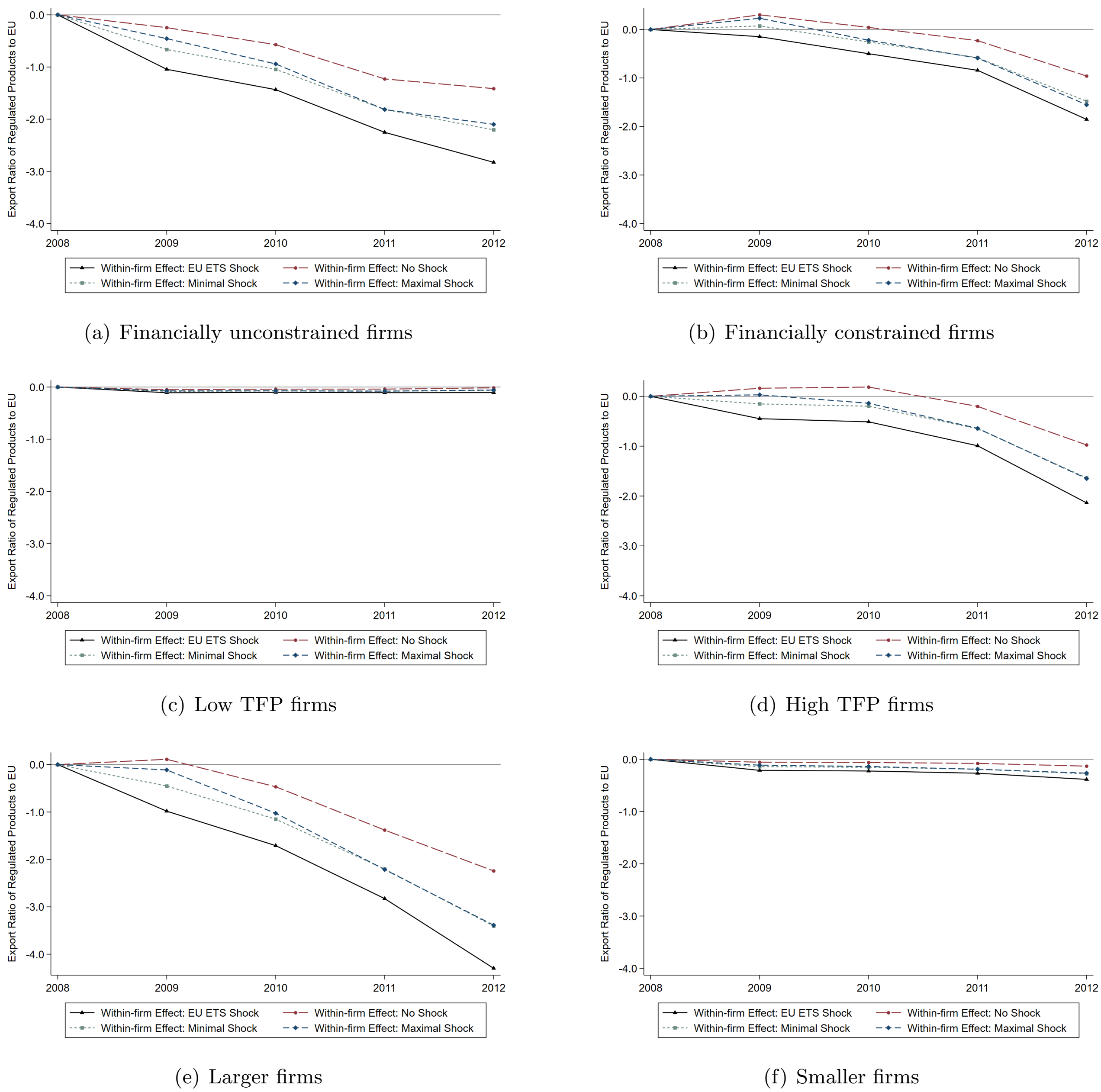
This further firm segmentation reinforces our empirical findings from the heterogeneity analysis: Firms that are financially unconstrained are more likely to adjust their EU export values in response to EU ETS price shocks. The differences between firms remain robust when considering the productivity level or firm size.

6 Conceptual theoretical framework

Our findings indicate that the EU ETS induced Chinese exporters to decrease export volume and value of regulated products to EU. In this section, we investigate the mechanisms that drive these results.

6.1 Setting and Utility Function

Following Chaney (2008), we assume there are N potentially asymmetric countries that produce goods using both labor and "dirty" inputs such as fossil fuels, which emit CO_2 when burned. Country n has a population L_n. Consumers in each country maximize utility derived from the consumption of goods from $H+1$ sectors. Sector 0 provides a single homogeneous good. The other H sectors are made of a continuum of differentiated goods. If a consumer consumes q_0 units of good 0, and $q_h(\omega)$ units of each



(a) Financially unconstrained firms

(b) Financially constrained firms

(c) Low TFP firms

(d) High TFP firms

(e) Larger firms

(f) Smaller firms

Figure 9: Within-firm Effect under different Shocks over phase II: Firm Heterogeneity

variety ω of good h, for all varieties in the set Ω_h (determined in equilibrium), he gets a utility U, as follows:

$$U \equiv q_0^{\mu_0} \prod_{h=1}^{H} \left(\int_{\Omega_h} q_h(\omega)^{(\sigma_h-1)/\sigma_h} \right)^{[\sigma_h/(\sigma_h-1)]\mu_h}, \qquad [8]$$

where $\mu_0 + \sum_{h=1}^{H} \mu_h = 1$ and $\sigma_h > 1$.

6.2 Trade Barriers and Technology

The homogeneous good 0 is freely traded and serves as the numeraire. It is produced with constant returns to scale with one unit of labor in country n producing w_n units of good 0. Its price is set equal to 1 so that if country n produces this good, the wage in country n is w_n.

Differentiated goods are produced using both labor and "dirty" inputs. The carbon price in country n, denoted t_n, is determined by the carbon trading system but is treated as exogenous in our analysis. According to the stylized facts as well as the regression results, we assume that there are two trading barriers: A variable cost τ_{ij}^h: If one unit of any differentiated good h is shipped from country i to country j, only a fraction $1/\tau_{ij}^h$ arrives; and a fixed cost f_{ij}^h: If a firm from country i in sector h exports to country j, it must pay a fixed cost f_{ij}^h.

All countries have access to the same technology. Each firm in sector h draws a random unit labor productivity φ. The cost of producing q units of a good and selling them in country j for a firm with productivity φ is

$$c_{ij}^h(q) = \frac{c(w_i, t_i)\,\tau_{ij}^h}{\varphi} q + f_{ij}^h, \qquad [9]$$

where $c(w_i, t_i)$ is an increasing function of wage w_i and carbon price t_i. For notation simplicity, we hereafter denote it as c_i. Then the marginal cost function is $c_{ij}^h(\varphi) = c_i \tau_{ij}^h / \varphi$. Since firms are price setters and the demand functions are isoelastic, the optimal price charged in country j by firm with productivity φ from country i is a constant mark-up over the unit cost (including transportation costs):

$$p_{ij}^h(\varphi) = \frac{\sigma_h}{\sigma_h - 1} \frac{c_i \tau_{ij}^h}{\varphi} = \frac{\sigma_h}{\sigma_h - 1} c_{ij}^h(\varphi). \qquad [10]$$

We then assume that productivity shocks are drawn from a Pareto distribution with shape parameter γ_h: productivity is distributed over $[1, +\infty)$ according to

$$\mathbb{P}(\tilde{\varphi}_h < \varphi) = G_h(\varphi) = 1 - \varphi^{-\gamma_h}, \qquad [11]$$

where $\gamma_h > \sigma_h - 1$ and $\gamma_h > 1$ so that the mean of the distribution exists. Following Chaney (2008), we assume the total mass of potential entrants in country n for each differentiated sector is proportional to $w_n L_n$, a simplification that implies larger, wealthier countries have more entrants. Besides, each worker owns w_n shares of a global fund, which collects profits from all firms and redistributes them in units of the numeraire good to its shareholders.

6.3 Demand for Differentiated Goods

The total income Y_j spent by workers in country j is the sum of their labor income $w_j L_j$ and of the dividends they get from their portfolio $\pi w_j L_j$, where π is a constant, representing the dividend per share of the global mutual fund. Given the optimal pricing of firms and the demand by consumers, exports from country i to country j in sector h, by a firm with productivity φ, are:

$$x_{ij}^h(\varphi) = p_{ij}^h(\varphi)\, q_{ij}^h(\varphi) = \mu_h Y_j \left(\frac{p_{ij}^h(\varphi)}{P_j^h}\right)^{1-\sigma_h}, \tag{12}$$

where P_j^h is the ideal price index for good h in country j. Finally, the ideal price index P_j^h for good h in country j and dividends per share π are defined as:

$$P_j^h = \left(\sum_{k=1}^{N} w_k L_k \int_{\bar{\varphi}_{kj}^h}^{\infty} \left(\frac{\sigma_h}{\sigma_h - 1}\frac{c_k \tau_{kj}^h}{\varphi}\right)^{1-\sigma_h} \mathrm{d}G_h(\varphi)\right)^{1/(1-\sigma_h)}, \tag{13}$$

and

$$\pi = \frac{\sum_{h=1}^{H}\sum_{l=1}^{N}\sum_{k=1}^{N} w_k L_k \left(\int_{\bar{\varphi}_{kj}^h}^{\infty} \pi_{kl}^h(\varphi)\, \mathrm{d}G_h(\varphi)\right)}{\sum_{n=1}^{N} w_n L_n}, \tag{14}$$

where $\pi_{kl}^h(\varphi) = \left(p_{kl}^h(\varphi) - c_{kl}^h(\varphi)\right) q_{kl}^h(\varphi) - f_{kl}^h$ are the net profits that a firm with productivity φ in country k and sector h earns from exporting to country l. For now, consider only sector h. The other sectors are analogous. For notation clarity, we drop the h subscript and all sector variables will refer to sector h when there is no ambiguity.

A firm chooses a subset of countries where it sells its output, and sets prices for its good in each market, taking the strategies of other firms and of consumers as given. Since we mainly focus on the intensive margin, we assume that firms optimize profits independently across destination markets and sectors. Consumers choose the quantity consumed of each variety available domestically, given prices. All agents move simultaneously, and an equilibrium is a fixed point to their strategies.

6.4 Productivity Threshold

We assume all industries are homogeneous. To simplify calculations and notation, we omit the sector index h. Given that wages are pinned down by sector 0 and the carbon price is exogenous, firms' profit utilities depend only on their productivity. By plugging the relationship of $c_{kl}(\varphi)$ with $p_{kl}(\varphi)$ into $\pi_{kl}(\varphi)$, the profits firm φ earns when exporting from i to j are:

$$\pi_{ij}(\varphi) = \frac{\mu}{\sigma} Y_j \left[\frac{\frac{\sigma}{\sigma-1}\frac{c_i \tau_{ij}}{\varphi}}{P_j} \right]^{1-\sigma} - f_{ij}.$$

Define the threshold $\bar{\varphi}_{ij}$ from $\pi_{ij}(\bar{\varphi}_{ij}) = 0$ as the productivity of the least productive firm in country i able to export to country j, we get:

$$\bar{\varphi}_{ij} = \lambda_1 \left(\frac{f_{ij}}{Y_j} \right)^{1/(\sigma-1)} \frac{c_i \tau_{ij}}{P_j}, \qquad [15]$$

where $\lambda_1 = (\sigma/\mu)^{1/(\sigma-1)} (\sigma/(\sigma-1))$. Also assume for all k and l, $\bar{\varphi}_{kl} > 1$ so that exporters are therefore only a subset of domestic firms.

6.5 Equilibrium Price Indices

Plugging the productivity thresholds from equation [15] into the price index from equation [13], the equilibrium price index is:

$$P_j = \lambda_2 \times Y_j^{\frac{1}{\gamma} - \frac{1}{\sigma-1}} \times \theta_j, \qquad [16]$$

where

$$\lambda_2^{\gamma} = \left(\frac{\gamma - (\sigma - 1)}{\gamma} \right) \left(\frac{\sigma}{\mu} \right)^{\gamma/(\sigma-1)-1} \left(\frac{\sigma}{\sigma - 1} \right)^{\gamma} \left(\frac{1+\pi}{Y} \right)$$

and

$$\theta_j^{-\gamma} = \sum_{k=1}^{N} \left(\frac{Y_k}{Y} \right) (c_k \tau_{kj})^{-\gamma} \times f_{kj}^{1-\gamma/(\sigma-1)}.$$

$Y = \sum_{k=1}^{N} Y_k$ is world output.

6.6 Equilibrium Exports and Profits

Substituting the general equilibrium price index from equation [16] into both the demand function and the productivity threshold from equation [15] allows for the simultaneous solution of firm-level exports, productivity thresholds, and total world profits.

Theorem 6.1: In general equilibrium, exports $x_{ij}(\varphi)$ from country i to country j by an individual firm with productivity φ, the productivity threshold $\bar{\varphi}_{ij}$ above which firms in i export to j, aggregate output Y_j, and dividends per share π are given as follows:

$$\begin{cases} x_{ij}(\varphi) & = \lambda_3 \times \left(\frac{Y_j}{Y}\right)^{(\sigma-1)/\gamma} \times \left(\frac{\theta_j}{c_i \tau_{ij}}\right)^{\sigma-1} \times \varphi^{\sigma-1} \times \mathbb{1}_{\{\varphi \geq \bar{\varphi}_{ij}\}}, \\ \bar{\varphi}_{ij} & = \lambda_4 \times \left(\frac{Y}{Y_j}\right)^{1/\gamma} \times \left(\frac{c_i \tau_{ij}}{\theta_j}\right) \times f_{ij}^{1/(\sigma-1)}, \\ Y_j & = (1+\pi) \times w_j L_j, \quad \text{and} \quad \pi = \frac{\sum_{h=1}^{H}\left(\frac{\sigma_h - 1}{\gamma_h}\right)\frac{\mu_h}{\sigma_h}}{1-\sum_{h=1}^{H}\left(\frac{\sigma_h - 1}{\gamma_h}\right)\frac{\mu_h}{\sigma_h}}, \end{cases}$$

where $\lambda_3 = \sigma \lambda_4^{1-\sigma}$, and $\lambda_4 = \left[\frac{\sigma}{\mu} \times \frac{\gamma}{\gamma-(\sigma-1)} \times \frac{1}{1+\pi}\right]^{1/\gamma}$.

6.7 Comparative Statics

From the equilibrium prices, price indices, and export levels derived above, we can generate several desirable predictions that align with our empirical findings.

Theorem 6.2: For a firm with productivity φ in home country i:

1. Its export price to country j is not related with the carbon price t_j:

$$\frac{\partial p_{ij}(\varphi)}{\partial t_j} = 0. \qquad [17]$$

2. Its export value to country j is positively related with the carbon price t_j:

$$\frac{\partial x_{ij}(\varphi)}{\partial t_j} > 0. \qquad [18]$$

   In conjunction with the property outlined above, the incremental impact of the carbon price arises solely from the equilibrium price index, hence the term “Global Ripples”.

3. The positive relationship between its export value to country j and the carbon price t_j is stronger when its productivity φ increases:

$$\frac{\partial^2 x_{ij}(\varphi)}{\partial t_j \partial \varphi} > 0. \qquad [19]$$

7 Conclusion

This paper investigates the spillover effects of the EU ETS on Chinese exporters, with particular emphasis on the international trade channel. Our findings reveal that declines in EU ETS prices lead to significant reductions in both export volume and value among Chinese exporters, whereas average export prices remain largely unchanged. This suggests that changes in market share, likely driven by competition in the EU market, serve as the primary transmission mechanism. Our theoretical analysis yields results consistent with the empirical analysis through a general equilibrium model. Under this framework, a firm's export price is unrelated to the carbon price of the importing country, but the export value exhibits a positive correlation with the importing country's carbon price. Moreover, this positive relationship strengthens with higher firm productivity, which is consistent with the "global ripple" effect.

Regarding firm heterogeneity, factors such as financial conditions productivity and size significantly influence the spillover effects. Financially unconstrained firms, firms with higher productivity and larger net income exhibit larger export adjustments, highlighting the importance of improving financing capability and productivity as well as maintaining sufficient liquidity to mitigate potential risks.

We also examine the implications of firm-level export changes at the aggregate level and find a positive relationship between export ratio of regulated products to the EU and the EU ETS prices. We further decompose this overall impact into three parts: The effect within the company, the effect between the companies and the effect of entry / exit, capturing changes in the export ratios of the firms over time, changes in the share of the market within affected product markets and the dynamics of entry and exit separately. Through decomposition analysis of changes in export ratios, we find that within-firm adjustments dominate observed export changes, while reallocation across firms and firm entry/exit dynamics contribute minimally to overall trends.

In the quantitative assessment section, various counterfactual scenarios further validate the positive relationship between export value and EU ETS shocks and provide additional policy implications. First, EU ETS prices have a significant effect on China's related exports. If the EU ETS price had remained at its 2008 peak, total export value would have increased by 10.8%. Second, within-firm effects contribute most to changes in export ratios. Across the four scenarios, within-firm effects account for a 2.4–4.7% decline in the overall export ratio, whereas between-firm effects are consistently positive. Third, fluctuations in EU ETS prices dominate the within-firm effect. Counterfactual results suggest that the precise level of the EU ETS price is not the main driver of firms' responses. Instead, uncertainty in the market discourages firms and reduces their export intensity. Fourth, the Matthew effect weakens as EU ETS prices decline. If the price had remained at its 2008 peak, firms with initially high export ratios in EU-affected markets would have gained even more market share relative to the observed outcomes.

Future research could extend the sample to encompass firms from a broader range of countries and regions, with a focus on exploring cross-industry and firm size heterogeneities in spillover effects. Additionally, it would be valuable to investigate how environmental regulations influence corporate innovation and long-term competitiveness, as these dynamics remain underexplored in the current analysis.

References

Abrell, Jan, Anta Ndoye Faye, and Georg Zachmann, "Assessing the impact of the EU ETS using firm level data," *Bruegel Working Paper*, 2011, (2011/08).

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

Aichele, Rahel and Gabriel Felbermayr, "Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade," *Review of Economics and Statistics*, March 2015, *97* (1), 104–115.

Amiti, M. and D. E. Weinstein, "Exports and financial shocks," *The Quarterly Journal of Economics*, 2011, *126* (4), 1841–1877.

Bartik, Timothy J., *Who Benefits from State and Local Economic Development Policies?*, W.E. Upjohn Institute, 1991.

Bartram, Söhnke M, Kewei Hou, and Sehoon Kim, "Real effects of climate policy: Financial constraints and spillovers," *Journal of Financial Economics*, 2022, *143* (2), 668–696.

Borghesi, Simone, Chiara Franco, and Giovanni Marin, "Outward foreign direct investment patterns of Italian firms in the European Union's Emission Trading Scheme," *Scandinavian Journal of Economics*, January 2020, *122* (1), 219–256.

Calel, Raphael and Antoine Dechezleprêtre, "Environmental policy and directed technological change: Evidence from the European carbon market," *Review of Economics and Statistics*, 2016, *98* (1), 173–191.

Chaney, Thomas, "Distorted gravity: the intensive and extensive margins of international trade," *American Economic Review*, 2008, *98* (4), 1707–1721.

Chen, Qiaoyi, Zhao Chen, Zhikuo Liu, Juan Carlos Suárez Serrato, and Daniel Yi Xu, "Regulating Conglomerates: Evidence from an Energy Conservation Program in China," *American Economic Review*, February 2025, *115* (2), 408–47.

Cherniwchan, Jevan and Nouri Najjar, "Do Environmental Regulations Affect the Decision to Export?," *American Economic Journal: Economic Policy*, May 2022, *14* (2), 125–60.

Colmer, Jonathan, Ralf Martin, Mirabelle Muûls, and Ulrich J Wagner, "Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading System," *The Review of Economic Studies*, 05 2024, *92* (3), 1625–1660.

Commins, Nicola, Seán Lyons, Marc Schiffbauer, and Richard SJ Tol, "Climate policy & corporate behavior," *The Energy Journal*, 2011, *32* (4), 51–68.

Copeland, Brian R. and M. Scott Taylor, "North–South trade and the environment," *The Quarterly Journal of Economics*, August 1994, *109* (3), 755–787.

Crinò, Rosario and Paolo Epifani, "Productivity, quality and export behaviour," *The Economic Journal*, 08 2012, *122* (565), 1206–1243.

Cui, Jingbo, Chunhua Wang, Junjie Zhang, and Yang Zheng, "The effectiveness of China's regional carbon market pilots in reducing firm emissions," *Proceedings of the National Academy of Sciences*, 2021, *118* (52), e2109912118.

Dechezleprêtre, Antoine, Daniel Nachtigall, and Frank Venmans, "The joint impact of the European Union emissions trading system on carbon emissions and economic performance," *Journal of Environmental Economics and Management*, 2023, *118*, 102758.

Ederington, Josh, Arik Levinson, and Jenny Minier, "Footloose and Pollution-Free," *Review of Economics and Statistics*, February 2005, *87* (1), 92–99.

Ellerman, A Denny, Claudio Marcantonini, and Aleksandar Zaklan, "The European Union emissions trading system: ten years and counting," *Review of Environmental Economics and Policy*, 2016.

Fan, Haichao, Edwin L.-C. Lai, and Yao Amber Li, "Credit constraints, quality, and export prices: Theory and evidence from China," *Journal of Comparative Economics*, 2015, *43* (2), 390–416.

Feenstra, Robert C., Zhiyuan Li, and Miaojie Yu, "Exports and credit constraints under incomplete information: Theory and evidence from China," *Review of Economics and Statistics*, 2014, *96* (4), 729–744.

Goldsmith-Pinkham, Paul, Isaac Sorkin, and Henry Swift, "Bartik instruments: What, when, why, and how," *American Economic Review*, 2020, *110* (8), 2586–2624.

Guariglia, Alessandra and Simona Mateut, "Inventory investment, global engagement, and financial constraints in the UK: Evidence from micro data," *Journal of Macroeconomics*, 2010, *32* (1), 239–250.

Kaplan, Steven N and Luigi Zingales, "Do investment-cash flow sensitivities provide useful measures of financing constraints?," *The Quarterly Journal of Economics*, 1997, *112* (1), 169–215.

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

Levinson, Arik and M. Scott Taylor, "Unmasking the Pollution Haven Effect," *International Economic Review*, February 2008, *49* (1), 223–254.

Liu, Yinan, Peiyao Lv, and Hao Zhao, "Green innovation through trade: The impact of the European Union Emissions Trading Scheme on Chinese exporters," *Journal of International Money and Finance*, 2024, *149*, 103215.

Manova, Kalina, "Credit constraints, heterogeneous firms, and international trade," *The Review of Economic Studies*, 2013, *80* (2), 711–744.

Manova, Kalina B., Shang-Jin Wei, and Zhiwei Zhang, "Firm exports and multinational activity under credit constraints," *Review of Economics and Statistics*, 2015, *97* (3), 574–588.

Martin, Ralf, Mirabelle Muûls, Laure B De Preux, and Ulrich J Wagner, "Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme," *American Economic Review*, 2014, *104* (8), 2482–2508.

_, Mirabelle Muûls, and Ulrich J. Wagner, "The impact of the European Union Emissions Trading Scheme on regulated firms: What is the evidence after ten years?," *Review of Environmental Economics and Policy*, 2016, *10* (1), 129–148.

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

Millimet, Daniel L. and Jayjit Roy, "Empirical Tests of the Pollution Haven Hypothesis When Environmental Regulation is Endogenous," *Journal of Applied Econometrics*, June 2016, *31* (4), 652–677.

Naegele, Helene and Aleksandar Zaklan, "Does the EU ETS Cause Carbon Leakage in European Manufacturing?," *Journal of Environmental Economics and Management*, 2019, *93*, 125–147.

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

Nordhaus, William D, "Economic growth and climate: the carbon dioxide problem," *The American Economic Review*, 1977, *67* (1), 341–346.

Oberndorfer, Ulrich, "EU emission allowances and the stock market: evidence from the electricity industry," *Ecological Economics*, 2009, *68* (4), 1116–1126.

Olley, GS and A Pakes, "The dynamics of productivity in the telecommunications equipment industry," *Econometrica*, 1996, *64* (6), 1263–1297.

Panon, Ludovic, "Labor share, foreign demand and superstar exporters," *Journal of International Economics*, 2022, *139*, 103678.

Pigou, A, *The Economics of Welfare. London: Macmillan and Co., ltd*, London : Macmillan and co., limited, 1920.

Sato, Misato and Antoine Dechezleprêtre, "Asymmetric industrial energy prices and international trade," *Energy Economics*, 2015, *52*, S130–S141.

Shi, Xinzheng and Zhufeng Xu, "Environmental regulation and firm exports: Evidence from the eleventh Five-Year Plan in China," *Journal of Environmental Economics and Management*, 2018, *89*, 187–200.

Topalova, Petia and Amit Khandelwal, "Trade liberalization and firm productivity: The case of India," *Review of Economics and Statistics*, 2011, *93* (3), 995–1009.

Verde, Stefano F., "The impact of the EU Emissions Trading System on competitiveness and carbon leakage: The econometric evidence," *Journal of Economic Surveys*, 2020, *34* (2), 320–343.

Wagner, Ulrich J. et al., "The causal effects of the European Union Emissions Trading Scheme: Evidence from French manufacturing plants," *Working Paper*, 2014.

Whited, Toni M and Guojun Wu, "Financial constraints risk," *The Review of Financial Studies*, 2006, *19* (2), 531–559.

A1 Sample Description

Table A1: Descriptive Statistics on Major Variables: Baseline Sample vs. Full Customs Sample

Variable	Obs.	Mean	Std. Dev.	Min	Max
Panel A: Baseline Regression Sample					
Ln(value)	564 786	9.517	2.716	0	21.872
Ln(quantity)	561 158	7.151	3.374	0	21.756
Ln(price)	561 158	2.404	2.381	-7.611	17.476
ETS_Shock^{export}	564 786	4.292	5.338	0	35.558
ETS_Shock^{import}	564 786	1.449	4.022	0	33.238
Panel B: Full Customs Sample					
Ln(value)	1 003 454	9.475	2.662	0	22.326
Ln(quantity)	997 364	7.129	3.332	0	22.189
Ln(price)	997 364	2.381	2.365	–7.611	17.476
ETS_Shock^{export}	1 003 454	4.370	5.603	0	62.316
ETS_Shock^{import}	1 003 454	1.433	4.125	0	33.238

Notes: The baseline regression focuses on within-firm effects and uses the matched firm-product-country-year export observations of firms exporting affected products to the EU. Panel A reports descriptive statistics of the matched sample, while Panel B reports the same statistics for all affected product exports to the EU in the customs dataset. Comparing Panels A and B shows that restricting to the matched sample does not compromise representativeness. We use the matched sample with balance-sheet data to construct TPU, financial constraint, and size dummies.

A2 Stylized Facts for Changing Denominator

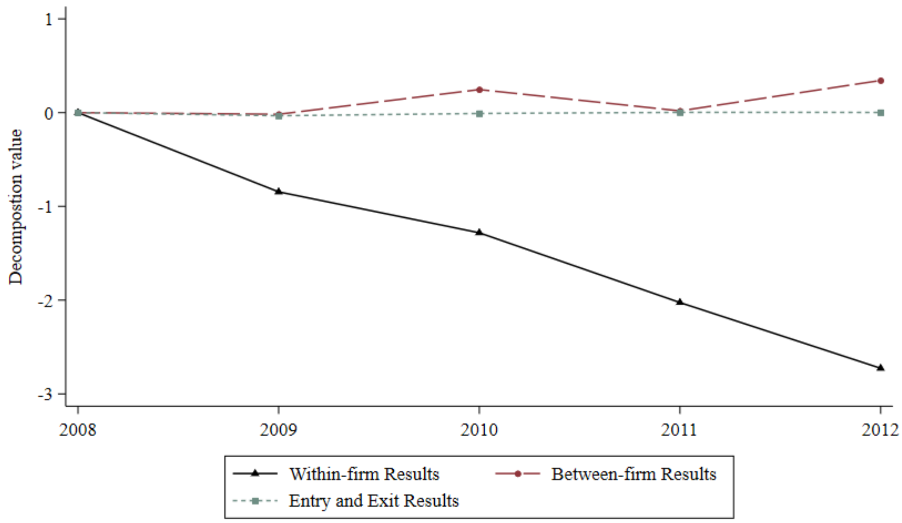


Figure A1: Decomposition of the Overall Export Ratio over the Years

A3 Robustness Checks

Table A2: Robustness Check: Excluding Industries Existing Before Phase I of the EU ETS

DEP. VAR.	(1) Ln(value)	(2) Ln(price)	(3) Ln(quantity)
ETS_Shock^{export}	0.020***	-0.001	0.020***
	(0.004)	(0.004)	(0.005)
Observations	170 798	170 197	170 197
R^2	0.335	0.656	0.515
Control variables	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
HS4–Year FE	Yes	Yes	Yes
Destination–Year FE	Yes	Yes	Yes

Notes: Robust standard errors are in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A3: Robustness Check: Checking the Exogeneity of EU ETS Price

DEP. VAR.	EU ETS price					
	(1)	(2)	(3)	(4)	(5)	(6)
Ln(value_Affected)	16.0201					
	(11.9159)					
L1.Ln(value_Affected)		10.9311				
		(14.5628)				
L2.Ln(value_Affected)			1.7412			
			(16.5847)			
Ln(value_Unaffected)				16.8492		
				(9.7325)		
L1.Ln(value_Unaffected)					12.6918	
					(8.7913)	
L2.Ln(value_Unaffected)						3.6766
						(7.6400)
Observations	36	35	34	36	35	34
R^2	0.8681	0.8398	0.8369	0.8618	0.8435	0.8378
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Dependent variable is EU ETS price measured in EUR. Robust standard errors are in parentheses. L1. and L2. denote the first and second lags, respectively. This regression shows that EU import in the related products won't change their EU ETS price significantly, ensuring the exogeneity of EU ETS price.

Table A4: Robustness Check: Using Euro-Denominated EU ETS Prices

DEP. VAR.	(1) Ln(value)	(2) Ln(price)	(3) Ln(quantity)
ETS_Shock^{export}	0.037***	0.002	0.034***
	(0.006)	(0.004)	(0.007)
Observations	448 865	445 341	445 341
R^2	0.347	0.656	0.468
Control variables	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
HS4–Year FE	Yes	Yes	Yes
Destination–Year FE	Yes	Yes	Yes

Notes: Robust standard errors are in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A5: Robustness Check: Accounting for the Impact of Global Financial Crisis

DEP. VAR.	(1) Ln(value)	(2) Ln(price)	(3) Ln(quantity)	(4) Ln(value)	(5) Ln(price)	(6) Ln(quantity)
ETS_Shock^{export}	0.010***	-0.003	0.013***	0.013***	0.002	0.010**
	(0.004)	(0.002)	(0.004)	(0.004)	(0.002)	(0.004)
Crisis Dummy × ETS_Shock^{export}	0.007***	0.004**	0.004			
	(0.002)	(0.001)	(0.002)			
US Exporter Dummy × ETS_Shock^{export}				0.013***	-0.000	0.014***
				(0.005)	(0.003)	(0.005)
Observations	552 019	548 471	548 471	552 019	548 471	548 471
R^2	0.354	0.677	0.497	0.354	0.677	0.497
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
HS4–Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Destination–Year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Robust standard errors are in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A6: Robustness Check: Reclassifying Products at the HS 2-Digit Level

DEP. VAR.	(1) Ln(value)	(2) Ln(price)	(3) Ln(quantity)
ETS_Shock^{export}	0.025***	0.001	0.023***
	(0.003)	(0.002)	(0.003)
Observations	363 573	362 110	362 110
R^2	0.393	0.664	0.498
Control variables	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
HS4–Year FE	Yes	Yes	Yes
Destination–Year FE	Yes	Yes	Yes

Notes: Robust standard errors are in parentheses. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

A4 Proof

Proof of equation [15]**:** Since we already know that

$$\pi_{ij}(\varphi) = \frac{\mu}{\sigma} Y_j \left[\frac{\frac{\sigma}{\sigma-1}\frac{c_i \tau_{ij}}{\varphi}}{P_j} \right]^{1-\sigma} - f_{ij}.$$

Let $\pi_{ij}(\bar{\varphi}_{ij}) = 0$, we have

$$\left[\frac{\frac{\sigma}{\sigma-1}\frac{c_i \tau_{ij}}{\varphi}}{P_j} \right]^{1-\sigma} = \frac{\sigma}{\mu}\frac{f_{ij}}{Y_j},$$

then

$$\frac{\sigma}{\sigma-1}\frac{c_i \tau_{ij}}{P_j}\frac{1}{\bar{\varphi}_{ij}} = \left(\frac{\sigma}{\mu}\right)^{1/(1-\sigma)} \left(\frac{f_{ij}}{Y_j}\right)^{1/(1-\sigma)},$$

finally

$$\bar{\varphi}_{ij} = \left(\frac{\sigma}{\mu}\right)^{1/(\sigma-1)} \frac{\sigma}{\sigma-1} \left(\frac{f_{ij}}{Y_j}\right)^{1/(\sigma-1)} \frac{c_i \tau_{ij}}{P_j},$$

which completes the proof. □

Proof of equation [16]**:** Plug the productivity thresholds from equation [15] into the price index from equation [13], and actually use the equilibrium equation $Y_j = (1+\pi) w_j L_j$, we have

$$P_j^h = \left(\sum_{k=1}^{N} w_k L_k \int_{\bar{\varphi}_{kj}^h}^{\infty} \left(\frac{\sigma_h}{\sigma_h - 1} \frac{c_k \tau_{kj}^h}{\varphi} \right)^{1-\sigma_h} \mathrm{d}G_h(\varphi) \right)^{1/(1-\sigma_h)}.$$

Omit the h subscript and all sector variables which refer to sector h, we then have

$$\begin{aligned}
P_j^{1-\sigma} &= \sum_{k=1}^{N} w_k L_k \int_{\bar{\varphi}_{kj}}^{\infty} \left(\frac{\sigma}{\sigma-1} \frac{c_k \tau_{kj}}{\varphi} \right)^{1-\sigma} \mathrm{d}G(\varphi) \\
&= \sum_{k=1}^{N} w_k L_k \int_{\bar{\varphi}_{kj}}^{\infty} \left(\frac{\sigma}{\sigma-1} \right)^{1-\sigma} (c_k \tau_{kj})^{1-\sigma} \varphi^{\sigma-1} \gamma \varphi^{-\gamma-1} \mathrm{d}\varphi \\
&= \sum_{k=1}^{N} w_k L_k \left(\frac{\sigma}{\sigma-1} \right)^{1-\sigma} (c_k \tau_{kj})^{1-\sigma} \frac{\gamma}{\sigma-1-\gamma} \varphi^{\sigma-1-\gamma} \Big|_{\bar{\varphi}_{kj}}^{\infty} \\
&= \sum_{k=1}^{N} w_k L_k \left(\frac{\sigma}{\sigma-1} \right)^{1-\sigma} (c_k \tau_{kj})^{1-\sigma} \frac{\gamma}{\gamma-(\sigma-1)} \bar{\varphi}_{kj}^{\sigma-1-\gamma}
\end{aligned}$$

$$
\begin{aligned}
&= \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} \frac{\gamma}{\gamma-(\sigma-1)} \sum_{k=1}^{N} \frac{Y_k}{1+\pi} \left(c_k \tau_{kj}\right)^{1-\sigma} \bar{\varphi}_{kj}^{\sigma-1-\gamma} \\
&= \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} \frac{\gamma}{\gamma-(\sigma-1)} \frac{Y}{1+\pi} \cdot \\
&\quad \sum_{k=1}^{N} \frac{Y_k}{Y} \left(c_k \tau_{kj}\right)^{1-\sigma} \left(\frac{\sigma}{\mu}\right)^{\frac{\sigma-1-\gamma}{\sigma-1}} \left(\frac{\sigma}{\sigma-1}\right)^{\sigma-1-\gamma} \left(\frac{f_{kj}}{Y_j}\right)^{\frac{\sigma-1-\gamma}{\sigma-1}} \left(\frac{c_k \tau_{kj}}{P_j}\right)^{\sigma-1-\gamma} \\
&= \left(\frac{\sigma}{\sigma-1}\right)^{-\gamma} \left(\frac{\sigma}{\mu}\right)^{\frac{\sigma-1-\gamma}{\sigma-1}} \frac{\gamma}{\gamma-(\sigma-1)} \frac{Y}{1+\pi} \cdot Y_j^{-\frac{\sigma-1-\gamma}{\sigma-1}} P_j^{1-\sigma+\gamma} \sum_{k=1}^{N} \frac{Y_k}{Y} \left(c_k \tau_{kj}\right)^{-\gamma} f_{kj}^{\frac{\sigma-1-\gamma}{\sigma-1}},
\end{aligned}
$$

then

$$
\begin{aligned}
P_j^{-\gamma} &= \left(\frac{\sigma}{\sigma-1}\right)^{-\gamma} \left(\frac{\sigma}{\mu}\right)^{\frac{\sigma-1-\gamma}{\sigma-1}} \frac{\gamma}{\gamma-(\sigma-1)} \frac{Y}{1+\pi} \cdot Y_j^{-\frac{\sigma-1-\gamma}{\sigma-1}} \sum_{k=1}^{N} \frac{Y_k}{Y} \left(c_k \tau_{kj}\right)^{-\gamma} f_{kj}^{1-\frac{\gamma}{\sigma-1}} \\
&= \left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right) \left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)-1} \left(\frac{\sigma}{\sigma-1}\right)^{\gamma} \left(\frac{1+\pi}{Y}\right)\right]^{-1} Y_j^{-\gamma\left(\frac{1}{\gamma}-\frac{1}{\sigma-1}\right)} \times \theta_j^{-\gamma} \\
&= \lambda_2^{-\gamma} Y_j^{-\gamma\left(\frac{1}{\gamma}-\frac{1}{\sigma-1}\right)} \times \theta_j^{-\gamma},
\end{aligned}
$$

thus the proof is completed. □

Proof of Theorem 6.1:

Firstly, plug the general equilibrium price index from equation [16] into the demand function [12], when $\varphi \geq \bar{\varphi}_{ij}$ we have

$$
\begin{aligned}
x_{ij}(\varphi) &= \mu Y_j \left(\frac{p_{ij}(\varphi)}{P_j}\right)^{1-\sigma} \\
&= \mu Y_j \left(\frac{\frac{\sigma}{\sigma-1} \frac{c_i \tau_{ij}}{\varphi}}{\lambda_2 \times Y_j^{\frac{1}{\gamma}-\frac{1}{\sigma-1}} \times \theta_j}\right)^{1-\sigma} \\
&= \mu \lambda_2^{\sigma-1} \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} Y_j Y_j^{(\sigma-1)\left(\frac{1}{\gamma}-\frac{1}{\sigma-1}\right)} \left(\frac{\theta_j}{c_i \tau_{ij}}\right)^{\sigma-1} \varphi^{\sigma-1} \\
&= \mu \left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right) \left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)-1} \left(\frac{\sigma}{\sigma-1}\right)^{\gamma} \left(\frac{1+\pi}{Y}\right)\right]^{\frac{\sigma-1}{\gamma}} \\
&\quad \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} Y_j^{\frac{\sigma-1}{\gamma}} \left(\frac{\theta_j}{c_i \tau_{ij}}\right)^{\sigma-1} \varphi^{\sigma-1} \\
&= \mu \left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right) \left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)-1} (1+\pi)\right]^{\frac{\sigma-1}{\gamma}} \\
&\quad \left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\gamma}} \left(\frac{\theta_j}{c_i \tau_{ij}}\right)^{\sigma-1} \varphi^{\sigma-1}
\end{aligned}
$$

$$
\begin{aligned}
&= \mu\frac{\sigma}{\mu}\left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right)\left(\frac{\sigma}{\mu}\right)^{-1}(1+\pi)\right]^{\frac{\sigma-1}{\gamma}}\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\gamma}}\left(\frac{\theta_j}{c_i\tau_{ij}}\right)^{\sigma-1}\varphi^{\sigma-1}\\
&= \sigma\left[\frac{\sigma}{\mu}\frac{\gamma}{\gamma-(\sigma-1)}\frac{1}{1+\pi}\right]^{\frac{1-\sigma}{\gamma}}\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\gamma}}\left(\frac{\theta_j}{c_i\tau_{ij}}\right)^{\sigma-1}\varphi^{\sigma-1}\\
&= \sigma\lambda_4^{1-\sigma}\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\gamma}}\left(\frac{\theta_j}{c_i\tau_{ij}}\right)^{\sigma-1}\varphi^{\sigma-1} = \lambda_3\left(\frac{Y_j}{Y}\right)^{\frac{\sigma-1}{\gamma}}\left(\frac{\theta_j}{c_i\tau_{ij}}\right)^{\sigma-1}\varphi^{\sigma-1}.
\end{aligned}
$$

When $\varphi < \bar{\varphi}_{ij}$, obviously $x_{ij}(\varphi) = 0$.

Secondly, plug the general equilibrium price index from equation [16] into the productivity threshold from equation [15], we have

$$
\begin{aligned}
\bar{\varphi}_{ij} &= \left(\frac{\sigma}{\mu}\right)^{1/(\sigma-1)}\frac{\sigma}{\sigma-1}\left(\frac{f_{ij}}{Y_j}\right)^{1/(\sigma-1)}\frac{c_i\tau_{ij}}{P_j}\\
&= \left(\frac{\sigma}{\mu}\right)^{1/(\sigma-1)}\frac{\sigma}{\sigma-1}\left(\frac{f_{ij}}{Y_j}\right)^{1/(\sigma-1)}\frac{c_i\tau_{ij}}{\lambda_2\times Y_j^{\frac{1}{\gamma}-\frac{1}{\sigma-1}}\times\theta_j}\\
&= \left(\frac{\sigma}{\mu}\right)^{1/(\sigma-1)}\frac{\sigma}{\sigma-1}Y_j^{-\frac{1}{\gamma}}\lambda_2^{-1}\frac{c_i\tau_{ij}}{\theta_j}f_{ij}^{1/(\sigma-1)}\\
&= \left(\frac{\sigma}{\mu}\right)^{1/(\sigma-1)}\frac{\sigma}{\sigma-1}Y_j^{-\frac{1}{\gamma}}\left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right)\left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)-1}\left(\frac{\sigma}{\sigma-1}\right)^{\gamma}\left(\frac{1+\pi}{Y}\right)\right]^{-\frac{1}{\gamma}}\frac{c_i\tau_{ij}}{\theta_j}f_{ij}^{1/(\sigma-1)}\\
&= \left(\frac{\sigma}{\mu}\right)^{1/(\sigma-1)}\left(\frac{Y}{Y_j}\right)^{\frac{1}{\gamma}}\left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right)\left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)-1}(1+\pi)\right]^{-\frac{1}{\gamma}}\frac{c_i\tau_{ij}}{\theta_j}f_{ij}^{1/(\sigma-1)}\\
&= \left[\left(\frac{\gamma-(\sigma-1)}{\gamma}\right)\left(\frac{\sigma}{\mu}\right)^{-1}(1+\pi)\right]^{-\frac{1}{\gamma}}\left(\frac{Y}{Y_j}\right)^{\frac{1}{\gamma}}\left(\frac{c_i\tau_{ij}}{\theta_j}\right)f_{ij}^{1/(\sigma-1)}\\
&= \left[\left(\frac{\gamma}{\gamma-(\sigma-1)}\right)\left(\frac{\sigma}{\mu}\right)\left(\frac{1}{1+\pi}\right)\right]^{\frac{1}{\gamma}}\left(\frac{Y}{Y_j}\right)^{\frac{1}{\gamma}}\left(\frac{c_i\tau_{ij}}{\theta_j}\right)f_{ij}^{1/(\sigma-1)} = \lambda_4\left(\frac{Y}{Y_j}\right)^{\frac{1}{\gamma}}\left(\frac{c_i\tau_{ij}}{\theta_j}\right)f_{ij}^{1/(\sigma-1)}.
\end{aligned}
$$

Thirdly, it is by definition that $Y_j = (1+\pi)\,w_jL_j$.

Finally, we calculate the dividend π. Notice that

$$
\begin{aligned}
\int_{\bar{\varphi}_{kl}}^{\infty}\pi_{kl}(\varphi)\,\mathrm{d}G(\varphi) &= \int_{\bar{\varphi}_{kl}}^{\infty}\left[\frac{\mu}{\sigma}Y_l\left(\frac{\frac{\sigma}{\sigma-1}\frac{c_k\tau_{kl}}{\varphi}}{P_l}\right)^{1-\sigma}-f_{kl}\right]\gamma\varphi^{-\gamma-1}\mathrm{d}\varphi\\
&= \int_{\bar{\varphi}_{kl}}^{\infty}\frac{\mu}{\sigma}Y_l\left(\frac{\sigma}{\sigma-1}\frac{c_k\tau_{kl}}{P_l}\right)^{1-\sigma}\gamma\varphi^{\sigma-\gamma-2}-f_{kl}\gamma\varphi^{-\gamma-1}\mathrm{d}\varphi\\
&= \frac{\mu}{\sigma}Y_l\left(\frac{\sigma}{\sigma-1}\frac{c_k\tau_{kl}}{P_l}\right)^{1-\sigma}\frac{\gamma}{\sigma-\gamma-1}\varphi^{\sigma-\gamma-1}+f_{kl}\varphi^{-\gamma}\Bigg|_{\bar{\varphi}_{kl}}^{\infty}\\
&= \frac{\mu}{\sigma}Y_l\left(\frac{\sigma}{\sigma-1}\frac{c_k\tau_{kl}}{P_l}\right)^{1-\sigma}\frac{\gamma}{\gamma-(\sigma-1)}\bar{\varphi}_{kl}^{\sigma-\gamma-1}-f_{kl}\bar{\varphi}_{kl}^{-\gamma}
\end{aligned}
$$

$$
\begin{aligned}
&= \frac{\mu}{\sigma} Y_l \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} \left(\frac{c_k \tau_{kl}}{\lambda_2 \times Y_l^{\frac{1}{\gamma}-\frac{1}{\sigma-1}} \times \theta_l}\right)^{1-\sigma} \\
&\quad \frac{\gamma}{\gamma-(\sigma-1)} \left(\lambda_4 \times \left(\frac{Y}{Y_l}\right)^{1/\gamma} \times \left(\frac{c_k \tau_{kl}}{\theta_l}\right) \times f_{kl}^{1/(\sigma-1)}\right)^{\sigma-\gamma-1} \\
&\quad - f_{kl} \left(\lambda_4 \times \left(\frac{Y}{Y_l}\right)^{1/\gamma} \times \left(\frac{c_k \tau_{kl}}{\theta_l}\right) \times f_{kl}^{1/(\sigma-1)}\right)^{-\gamma} \\
&= \frac{\mu}{\sigma} Y_l^{\frac{\sigma-1}{\gamma}} \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} \lambda_2^{\sigma-1} \lambda_4^{-\gamma} \left(\frac{c_k \tau_{kl}}{\theta_l}\right)^{-\gamma} f_{kl}^{1-\frac{\gamma}{\sigma-1}} \\
&\quad \frac{\gamma}{\gamma-(\sigma-1)} \lambda_4^{\sigma-1} \left(\frac{Y}{Y_l}\right)^{\frac{\sigma-\gamma-1}{\gamma}} \\
&\quad - \lambda_4^{-\gamma} \left(\frac{Y_l}{Y}\right) f_{kl}^{1-\frac{\gamma}{\sigma-1}} \left(c_k \tau_{kl}\right)^{-\gamma} \theta_l^{\gamma} \\
&= \left(\frac{\mu}{\sigma} Y^{\frac{\sigma-1}{\gamma}} \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} \lambda_2^{\sigma-1} \frac{\gamma}{\gamma-(\sigma-1)} \lambda_4^{\sigma-1} - 1\right) \\
&\quad \lambda_4^{-\gamma} \left(\frac{Y_l}{Y}\right) f_{kl}^{1-\frac{\gamma}{\sigma-1}} \left(c_k \tau_{kl}\right)^{-\gamma} \theta_l^{\gamma},
\end{aligned}
$$

where

$$
\begin{aligned}
&\frac{\mu}{\sigma} Y^{\frac{\sigma-1}{\gamma}} \left(\frac{\sigma}{\sigma-1}\right)^{1-\sigma} \lambda_2^{\sigma-1} \lambda_4^{\sigma-1} = \frac{\mu}{\sigma} \left[\left(\frac{\sigma}{\sigma-1}\right)^{-\gamma} \lambda_2^{\gamma} \lambda_4^{\gamma} Y\right]^{\frac{\sigma-1}{\gamma}} \\
&= \frac{\mu}{\sigma} \left[\left(\frac{\sigma}{\sigma-1}\right)^{-\gamma} \left(\frac{\gamma-(\sigma-1)}{\gamma}\right) \left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)-1} \left(\frac{\sigma}{\sigma-1}\right)^{\gamma} \left(\frac{1+\pi}{Y}\right) \frac{\sigma}{\mu} \times \frac{\gamma}{\gamma-(\sigma-1)} \times \frac{1}{1+\pi} Y\right]^{\frac{\sigma-1}{\gamma}} \\
&= \frac{\mu}{\sigma} \left[\left(\frac{\sigma}{\mu}\right)^{\gamma/(\sigma-1)}\right]^{\frac{\sigma-1}{\gamma}} = 1,
\end{aligned}
$$

then

$$
\begin{aligned}
\int_{\bar{\varphi}_{kl}}^{\infty} \pi_{kl}(\varphi)\, \mathrm{d}G(\varphi) &= \left(\frac{\gamma}{\gamma-(\sigma-1)} - 1\right) \lambda_4^{-\gamma} \left(\frac{Y_l}{Y}\right) f_{kl}^{1-\frac{\gamma}{\sigma-1}} \left(c_k \tau_{kl}\right)^{-\gamma} \theta_l^{\gamma} \\
&= \frac{\sigma-1}{\gamma-(\sigma-1)} \lambda_4^{-\gamma} \left(\frac{Y_l}{Y}\right) f_{kl}^{1-\frac{\gamma}{\sigma-1}} \left(c_k \tau_{kl}\right)^{-\gamma} \theta_l^{\gamma}.
\end{aligned}
$$

Therefore combine $Y_j = (1+\pi) w_j L_j$, we have

$$
\begin{aligned}
&\sum_{l=1}^{N} \sum_{k=1}^{N} w_k L_k \left(\int_{\bar{\varphi}_{kj}^{h}}^{\infty} \pi_{kl}^{h}(\varphi)\, \mathrm{d}G_h(\varphi)\right) \\
&= \sum_{l=1}^{N} \sum_{k=1}^{N} w_k L_k \frac{\sigma-1}{\gamma-(\sigma-1)} \lambda_4^{-\gamma} \left(\frac{Y_l}{Y}\right) f_{kl}^{1-\frac{\gamma}{\sigma-1}} \left(c_k \tau_{kl}\right)^{-\gamma} \theta_l^{\gamma}
\end{aligned}
$$

$$
\begin{aligned}
&= \frac{\sigma-1}{\gamma-(\sigma-1)}\lambda_4^{-\gamma}\sum_{l=1}^{N}\theta_l^{\gamma}\sum_{k=1}^{N}w_kL_k\left(\frac{Y_l}{Y}\right)f_{kl}^{1-\frac{\gamma}{\sigma-1}}\left(c_k\tau_{kl}\right)^{-\gamma}\\
&= \frac{\sigma-1}{\gamma-(\sigma-1)}\lambda_4^{-\gamma}\sum_{l=1}^{N}\theta_l^{\gamma}\sum_{k=1}^{N}\frac{Y_k}{1+\pi}\left(\frac{Y_l}{Y}\right)f_{kl}^{1-\frac{\gamma}{\sigma-1}}\left(c_k\tau_{kl}\right)^{-\gamma}\\
&= \frac{\sigma-1}{\gamma-(\sigma-1)}\lambda_4^{-\gamma}\sum_{l=1}^{N}\theta_l^{\gamma}\frac{Y_l}{1+\pi}\sum_{k=1}^{N}\left(\frac{Y_k}{Y}\right)f_{kl}^{1-\frac{\gamma}{\sigma-1}}\left(c_k\tau_{kl}\right)^{-\gamma}\\
&= \frac{\sigma-1}{\gamma-(\sigma-1)}\lambda_4^{-\gamma}\sum_{l=1}^{N}\theta_l^{\gamma}\frac{Y_l}{1+\pi}\theta_l^{-\gamma} = \frac{\sigma-1}{\gamma-(\sigma-1)}\lambda_4^{-\gamma}\sum_{l=1}^{N}w_lL_l\\
&= \frac{\sigma-1}{\gamma-(\sigma-1)}\left[\frac{\sigma}{\mu}\times\frac{\gamma}{\gamma-(\sigma-1)}\times\frac{1}{1+\pi}\right]^{-1}\sum_{l=1}^{N}w_lL_l\\
&= \frac{\sigma-1}{\gamma}\frac{\mu}{\sigma}\left(1+\pi\right)\sum_{l=1}^{N}w_lL_l = \frac{\sigma-1}{\gamma}\frac{\mu}{\sigma}\left(1+\pi\right)\sum_{n=1}^{N}w_nL_n.
\end{aligned}
$$

Therefore by adding the h subscript, we have

$$
\begin{aligned}
\pi &= \frac{\sum_{h=1}^{H}\sum_{l=1}^{N}\sum_{k=1}^{N}w_kL_k\left(\int_{\bar{\varphi}_{kj}^{h}}^{\infty}\pi_{kl}^{h}\left(\varphi\right)\mathrm{d}G_h\left(\varphi\right)\right)}{\sum_{n=1}^{N}w_nL_n}\\
&= \frac{\sum_{h=1}^{H}\frac{\sigma_h-1}{\gamma_h}\frac{\mu_h}{\sigma_h}\left(1+\pi\right)\sum_{n=1}^{N}w_nL_n}{\sum_{n=1}^{N}w_nL_n} = \left(1+\pi\right)\sum_{h=1}^{H}\frac{\sigma_h-1}{\gamma_h}\frac{\mu_h}{\sigma_h},
\end{aligned}
$$

thus

$$
\pi = \frac{\sum_{h=1}^{H}\frac{\sigma_h-1}{\gamma_h}\frac{\mu_h}{\sigma_h}}{1-\sum_{h=1}^{H}\frac{\sigma_h-1}{\gamma_h}\frac{\mu_h}{\sigma_h}}.
$$

□

Proof of Theorem 6.2:

Firstly, we have already shown that

$$
p_{ij}\left(\varphi\right) = \frac{\sigma_h}{\sigma_h-1}\frac{c\left(w_i,t_i\right)\tau_{ij}^{h}}{\varphi},
$$

where $c\left(w_i,t_i\right)$ is an increasing function of wage w_i and carbon price t_i. Since the expression does not include t_j for $i\neq j$, it is obvious that $\partial p_{ij}\left(\varphi\right)/t_j = 0$.

Secondly, notice that we can express $x_{ij}\left(\varphi\right)$ as

$$
x_{ij}\left(\varphi\right) = \lambda_3\times\left(\frac{Y_j}{Y}\right)^{(\sigma-1)/\gamma}\times\left(\frac{\theta_j}{c_i\tau_{ij}}\right)^{\sigma-1}\times\varphi^{\sigma-1}\times\mathbb{1}_{\{\varphi\geq\bar{\varphi}_{ij}\}}
$$

$$= \lambda_3 \times \left(\frac{Y_j}{Y} \theta_j^{\gamma} \left(c_i \tau_{ij} \right)^{-\gamma} \right)^{(\sigma-1)/\gamma} \times \varphi^{\sigma-1} \times \mathbb{1}_{\{\varphi \geq \bar{\varphi}_{ij}\}} \propto \theta_j^{\gamma},$$

since $\sigma > 1$ and $\gamma > 0$. Also notice that

$$\theta_j^{-\gamma} = \sum_{k=1}^{N} \left(\frac{Y_k}{Y} \right) \left(c_k \tau_{kj} \right)^{-\gamma} \times f_{kj}^{1-\gamma/(\sigma-1)}.$$

Therefore, when t_j increases, c_j increases, thus $c_j^{-\gamma}$ decreases, then $\theta_j^{-\gamma}$ decreases, thus θ_j^{γ} increases, finally $x_{ij}(\varphi)$ increases. Therefore, we can conclude that (when $\varphi \geq \bar{\varphi}_{ij}$,) $\partial x_{ij}(\varphi)/t_j = 0$.

Thirdly, notice that (when $\varphi \geq \bar{\varphi}_{ij}$,)

$$\frac{\partial x_{ij}(\varphi)}{\partial \varphi} = \frac{\sigma - 1}{\varphi} x_{ij}(\varphi).$$

Therefore,

$$\frac{\partial^2 x_{ij}(\varphi)}{\partial t_j \partial \varphi} = \frac{\sigma - 1}{\varphi} \frac{\partial x_{ij}(\varphi)}{\partial t_j} > 0.$$

□