Carbon Pricing and Trade Diversion

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Abstract

This paper examines the impact of carbon pricing on the trading patterns of firms and the overall effect on CO_2 emissions embedded in their imports. We exploit carbon policy shocks, which are identified using high-frequency identification in combination with French administrative trade data and CO_2 emission databases. We show that a tighter carbon pricing regime of the European Union Emission Trading System disproportionately increases imports from countries outside of the carbon price domain. However, this effect is not permanent and does not lead to persistent changes in trading patterns. We document that while CO_2 emissions embedded in imports increase, this increase is slower than the response in value of trade, and firms mainly substitute towards imports of less CO_2-intensive inputs. Finally, we show that policies for specific, mostly carbon-intensive, products and industries aimed at preventing carbon leakage are successful in their core objective.

Keywords: Climate policies, Carbon pricing, International Trade.
JEL classification: F14, F18, Q43, Q54

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1 Introduction

Limiting climate change and reducing greenhouse gas emissions is a major challenge for humanity in the 21st century. While a general rise in average temperature seems unavoidable, the exact increase is still to be determined and ultimately depends on today's policies. Economists consider carbon pricing as one of the most, if not the most, efficient tools in limiting greenhouse gas emissions following a classical Coasian argument. Such a price, implemented either with a direct tax on carbon emissions or through a cap-and-trade system, ensures an efficient path of emission reductions. A global price on carbon emissions would not only limit the overall emissions but would guarantee that the emissions with the lowest abatement cost are cut.

Global policy coordination has proven notoriously difficult due to the externalities associated with greenhouse gas emissions. As a result, various unilateral approaches to carbon pricing have emerged, with one prominent example being the European Union Emission Trading System (EU-ETS). However, these approaches are often incomplete: they lack a Carbon Border Adjustment Mechanism (CBAM), and thus, their effectiveness is potentially threatened in a globalized world where production is mobile and supply chains are well developed. A substantial amount of global carbon dioxide (CO_2) emissions is tied to international trade flows. In 2018, according to OECD statistics, the EU-27's gross imports contained 1.2 billion tonnes of CO_2, while the EU's domestic production emitted 3.4 billion tonnes of CO_2. Consequently, a significant share of the latter emissions falls under the purview of the EU-ETS, while this does not necessarily hold true for all imports. This asymmetry creates an intuitive imbalance, rendering production within the EU-ETS more expensive and reducing the relative cost of imports, making them a more appealing option. This phenomenon, characterized by avoiding CO_2 pricing and its associated environmental consequences, is commonly referred to as carbon leakage. However, the empirical evidence supporting the significance of this issue remains limited, and an ongoing academic and political debate revolves around how best to address this challenge proactively. The EU Commission acknowledges this incompleteness and prepares the introduction of a CBAM.

This paper aims to contribute to this discussion by analyzing how changes in the tightness of carbon policies and resulting carbon price reactions of the EU-ETS affect firms' trading patterns. We assess both the effects on the value of imports as well as the overall CO_2 emissions embedded in these trade flows. We measure exogenous changes in the carbon price using the carbon policy shock series developed in Känzig (2022). To evaluate how firms' trade flows are affected by carbon pricing policies, we combine the carbon policy shock series with French firm-level administrative and customs data. We extend the analysis to overall emissions by using both Exiobase and Ecoinvent data. Exiobase and Ecoinvent are datasets that aim to capture the CO_2 emissions embedded in production on a product-country level. While Exiobase is more aggregate and exhaustive, Ecoinvent is more granular and focuses on intermediate products. They complement each other in many dimensions, which we outline later in the paper. The empirical specification we adopt is a panel local projection à la Jordà (2005). This approach has several advantages as it allows to estimate an impulse response function and, consequently, the timing of the firm's response. Further, these estimates capture the overall effects of carbon policy changes, including general equilibrium effects.

We document that firms' import decisions respond to carbon policy shocks. Firms import more from countries that are not part of the EU-ETS following a carbon policy surprise, tightening the carbon pricing regime. In contrast, trade from EU-ETS member countries stays flat or even declines. Quantitatively, this means that the firms' imports from countries not participating in the EU-ETS increase by up to 3.5% about three years after a shock that increases energy prices by 1% due to an increase in carbon prices. Trade from countries participating in the ETS declines by up to 2.5%. However, these effects are temporary and fade out. To further investigate carbon leakage, we show that the response in trade volume is also mirrored by CO2 emissions embedded in these import flows. Interestingly, this increase is weaker, suggesting that less CO_2-intense products drive the trade response. Overall emissions embedded in imports from countries not participating in the EU-ETS increase by up to 2.5% about three years after the shock. We analyze a set of policy measures that are in place for a subset of carbon-intensive industries/products to limit carbon leakage. We find that there is no increase in imports from outside the EU-ETS of products that qualify for these policies. This is suggestive evidence that these measures indeed help to attenuate import substitution and contribute to the muted response of CO_2 emissions. However, these policies come at a cost, e.g., free handouts of emission certificates. Therefore, despite these measures fulfilling their purpose, our results highlight the potential efficiency gains of a Carbon Border Adjustment Mechanism to limit trade reactions and to increase the overall economic as well as environmental efficiency of the EU-ETS.

Related literature Our first contribution to the literature is to estimate carbon leakage in response to environmental regulation. Carbon leakage is a particular case of the pollution haven hypothesis. Although there is extensive literature on the pollution haven literature, the empirical evidence for carbon leakage is still limited, and results are mixed, depending on the context and specific study. Furthermore, there are different ways in which carbon leakage is defined in the literature, making comparisons more difficult. Typically, carbon leakage is measured as additional emissions abroad relative to domestic emissions savings. Carbon leakage of 100% means that all the emissions saved domestically are instead emitted abroad, which brings the global savings in emissions to zero. Carbon leakage can happen through different channels, e.g., through emissions embedded in trade but also through shifting energy demand affecting global energy prices (Yu et al., 2021). In this paper, we focus on the trade channel. Previous studies have used different techniques and data and also did not estimate carbon leakage as the percentage increase in embedded trade emissions using this level of granularity.

There is previous work that aims to estimate carbon leakage under the EU-ETS. Muûls et al. (2022) compare firms that, due to their industry and installations, directly fall under the EU-ETS and consequently have to buy emission certificates with unregulated firms using a matched difference-in-difference design. They find no evidence of carbon leakage but a substantial reduction in CO_2 intensity. They argue that this can be rationalized in a framework of firms being inattentive to the returns on investment in clean technology and, therefore, underinvest. Several key differences in our approach can explain the different results. First, there are methodological differences: Our approach is to leverage aggregate carbon policy surprises to use local projections compared to the difference-in-difference strategy in their paper. While the latter allows for a detailed comparison of firms that are required to buy emission certificates and those who do not, our approach allows us to capture general equilibrium effects. An important channel of how carbon prices affect the overall economy is through energy prices. Through this channel, all companies in the economy are affected, and this cancels out in a difference-in-difference comparison. Further, we argue that, especially for imports, the difference is not to be expected between companies that fall under the EU-ETS and those that don't, but rather between products that are getting more expensive either through the direct costs of carbon emission certificates or through increasing energy prices. Second, their setting aims to capture the overall effect of the introduction of the EU-ETS, while our approach aims to capture the effect of marginal changes in the carbon price of an existing scheme, making the studies complementary.

Several studies investigate carbon leakage of emission-intensive, trade-exposed industries in the EU-ETS and generally find small or zero carbon leakage (see, e.g., Venmans et al., 2020 for a review). Dechezleprêtre et al. (2022) investigate the effect on multinational firms, where we would expect that emissions are more easily moved to their plants abroad. They find no evidence for a reallocation of CO_2 emissions. The paper leverages data from 2007 until 2014 when carbon prices were very low, and the free allocation of certificates was more important than in the later stages of the EU-ETS. Further, it looks at a particular channel of within-firm substitution and not the whole supply chain.

Other studies analyzed the EU-ETS, focusing on different mechanisms and channels of Carbon Leakage. D'Arcangelo and Galeotti (2022) analyze the effect of the EU ETS on carbon leakage, focusing on cross-country investments. They show that investments react to carbon pricing and that the effect is stronger for more polluting investments. However, the aggregate amount of diverted investments is small. Our paper, in contrast, looks at the trade channel of Carbon Leakage. In their review of the literature Venmans et al. (2020) find robust positive effects on innovation, especially on patenting activity. The literature is not restricted to the assessment of the EU-ETS. Aichele and Felbermayr (2015) analyze aggregate cross-country/sectoral trade flows and estimate carbon leakage associated with the Kyoto Protocol. The Kyoto Protocol was implemented with different policies across countries. The authors do identify carbon leakage and estimate that imports from non-ratifying countries increase by 5%, which results in an 8% higher CO_2 content. While this paper, therefore, assesses the effect of introducing a policy package consisting of a wide range of measures, our approach allows us to estimate the effect of marginally adjusting an existing policy.

Another approach to estimating carbon leakage is to use computational general equilibrium models. This approach has the advantage of potentially taking several channels of carbon leakage into account. In a review Yu et al. (2021) find that typical carbon leakage estimates in this literature are between 5% and 30%, with both the energy price channel and the trade channel playing an important role. These modes have the advantage of explicitly modeling the introduction and potential channels of carbon prices. Delivering an exogenous measure for a firm's trade reaction to carbon policy shocks estimated in this paper can be used as input to improve the fit of these models.

Känzig (2022) developed the identification and carbon policy surprise series used in this paper. He shows that low-income households are over-proportionally affected by carbon price shocks, mainly through general equilibrium effects. He further documents more green innovation. Building on this work, several papers have already emerged extending this analysis. Mangiante (2023) document that poorer Euro Area countries' economic activity is more strongly affected. Berthold et al. (2023) show that economic activity in more CO_2 intensive countries is more affected by carbon pricing policies. Hensel et al. (2023) outline that firms' inflation expectations increase significantly in reaction to the shock. However, firms overestimate the effect, which leads to a positive forecast error in the medium term. We complement this literature stream by providing evidence of the potential trade effects of carbon prices on a firm level.

In contrast to previous empirical studies on carbon leakage that rely, e.g., on a difference-in-difference framework or similar identification methods, our empirical approach captures the general equilibrium effects of carbon price changes. Primarily through the spillover effects of energy prices, they not only affect companies who are directly responsible for emissions and are subject to the emission trading system but essentially all companies through their energy consumption. Further, using linear projections allows us to trace firm-level carbon leakage responses over time.

Road map. The paper is structured as follows. Section 2 provides a comprehensive overview of the relevant features of the EU-ETS, chapter 3 outlines the data used, Chapter 4 shows the effects of the Carbon Price Shocks on key macroeconomic variables, Chapter 5 presents the empirical strategy, and Chapter 6 summarises the main results. Chapter 7 discusses potential caveats, and chapter 8 concludes.

2 The EU-ETS

> *"The EU-ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively."*
>
> EU Commission

The EU-ETS operates under a cap and trade system, meaning that not the price but the quantity of greenhouse gas emissions is fixed. The price is then set through an auction mechanism. Companies that are regulated under the EU-ETS are required to obtain sufficient certificates for their greenhouse emissions. These are checked annually and are subject to fines if the account is not balanced. As long as the maximum quantity of emissions certificates is a binding constraint, this mechanism ensures a positive price. The system was introduced in 2005 and has undergone both significant changes and minor revisions over time. The major changes can be divided into 4 phases of the EU-ETS, with the first phase spanning from 2005-2007, phase 2 from 2008-2012, phase 3 from 2012-2020, and phase 4 from 2021-2030. The first phase was designed as a learning-by-doing stage, and most emission certificates were allocated for free. It was restricted to activities related to power generators and energy-intensive industries. The aim was to put the infrastructure and monitoring in place. Furthermore, there was not one cap for the overall ETS domain but for each country, which was based on estimates. These turned out to be too generous, and the price eventually fell to zero as they were also not allowed to be carried over to the second stage. A primary objective of this stage was to get data on total emissions, which could then be used to determine the cap in the subsequent phases. The second phase expanded the scope of activities, installations, and companies covered under the EU-ETS, reduced the amount of emission certificates, and reduced the share of allowances allocated for free. Phase 3 replaced the national caps with an EU-ETS-wide cap, replaced the free allocation of allowances for many industries with an auction mechanism, and further expanded the scope of covered activities. The EU Commission formally adopted the latest major reform of the EU-ETS in April 2023. The main target is the gradual phase-out of free allowances still granted to industries/products deemed to be at high risk of Carbon leakage. In parallel with the phase-out of free allowances, a so-called carbon border adjustment mechanism (CBAM) will be implemented to reduce the risk of carbon leakage. Under the CBAM, emissions embedded in imports will be taxed; however, exports out of the EU will not be subsidized. Hence, weighing the internalization of the external costs of carbon higher than the competitive disadvantage that European firms face on global markets. In addition, the reform consists of a more ambitious reduction path that aligns with the EU's new climate goals, the gradual inclusion of additional sectors, and the creation of separate new ETS for buildings, roads, transport, and fuels.

Today, about 45% of European greenhouse emissions are covered by the EU-ETS. The EU-ETS covers approximately 10,000 companies and installations. Globally, the EU-ETS only plays a minor role, which is decreasing over time, covering 2.81% of global emissions in 2019, down from 4.85% in 2005. This decrease in coverage is primarily due to the EU emitting a smaller share of global emissions in 2019.

Concerns for Carbon Leakage have been a central issue considered in the design of the EU-ETS. The European Commission incorporated measures in the cap and trade system intending to prevent carbon leakage. As a result, specific products/industries at risk of carbon leakage are identified. The EU Commission considers two characteristics to be the main determinants of carbon leakage risk: First, the additional costs incurred due to the implementation of the EU-ETS, and second, the sector's reliance on trade and exposure to international competition. The additional costs are measured relative to gross value added, considering if an industry would be eligible for a share of free allowances independent of its carbon leakage risk. Costs include direct costs of the emission allowances and indirect costs through, e.g., higher electricity prices. Reliance on trade and competitiveness is measured as the share of imports and exports of a sector relative to domestic production plus imports (Graichen, V., et al. 2017). Sectors (4-digit nace) or subsectors (6-digit CPA) are deemed at risk of carbon leakage if they satisfy one of the following criteria. [1]:

- If the share of additional costs exceeds 30%
- If the trade intensity exceeds 30%
- If the share of additional cost exceeds 5% *and* trade intensity is above 10%

Sectors and subsectors that satisfy one of these criteria are eligible to receive up to 100% of their required emission allowances for free. The exact share is determined using a formula incorporating production quantity and a benchmark value for that particular product (measured in emissions per tonne). It is worth noting that other industries were also eligible for free allowances, although for a lower share, which has been reduced annually since 2013.

In addition, countries are allowed to compensate specific industries that face high indirect costs up to a certain threshold.

2.1 Carbon Policy Shock Series

We exploit the carbon policy surprise developed by Känzig (2022). The identification strategy and the mechanics of this shock are similar to the identification of monetary policy surprises. (see, among others, Gürkaynak et al., 2005 and Nakamura and Steinsson, 2018). It relies on the availability of high-frequency price data around special events. Monetary policy shocks rely on asset price (e.g., bonds) fluctuations in a narrow time window around the announcements of monetary policy decisions. In case of carbon policy surprises, the counterparts for monetary policy decisions are policy decisions by the European Parliament, the European Commission, or European Courts that affect the supply of carbon emission certificates. These include, e.g., decisions regarding the free allocation of certificates, the auction of allowances, and the use of international credits. The counterpart of asses price movements are changes in the future prices of carbon emission allowances. Känzig (2022) identifies 126 of those events from 2005 to

[1] For a few sectors and subsectors a qualitative assessment was carried out.

Table 1: Descriptive Statistics of carbon price surprises and the resulting shock

	N	Mean	Std. Dev.	Min	Max
Surprise	246	-0.023	0.221	-2.007	1.532
Shock	246	0.000	0.630	-1.333	1.335

Notes: Surprises are identified directly around the announcement windows, while shocks are the structural shock series identified through an external instrument VAR approach with the surprises as an instrument. Both were supplied by Känzig (2022)

2019. These events reveal information to market participants, and when looking at the market reactions in a tight time frame around the event, these can be interpreted as an unexpected and exogenous price change solely driven by the event.

Surprises in carbon policy are calculated by examining fluctuations in the future prices of EU emission allowances (EUAs) within the ICE market, which is the most liquid future market. More specifically, these surprises are characterized by the variations in the EUR value of carbon prices in relation to the wholesale electricity price prevailing on the day preceding the specific event. The daily surprises are then summed to a monthly series. In months with no regulatory events, the series has a value of zero.

Since it is hard to argue that the identified events are exhaustive and cover all such relevant events, the resulting surprise series is prone to measurement error. Therefore, the standard in the literature is to use the surprise series as an IV for a Vector Auto Regression. This VAR covers the period from 1999 to 2019. It includes the energy component of the HICP (for which the Instrument is used), total GHG emissions, the headline HICP, industrial production, the unemployment rate, the policy rate, a stock market index, and the real effective exchange rate.

The carbon policy shocks are then extracted from the residuals of the monthly VAR (see Stock and Watson, 2018) and normalized to increase the energy component of the HICP by one percent on impact. Carbon policy surprises of this magnitude were observed in the time frame concerned.

If the procedure is successful, this shock series is truly exogenous to everything else that affects the economy. While this is impossible to test and verify, Känzig (2022) conducts several checks. For one, they are mean zero and not serially correlated.

They are also not forecastable by past macroeconomic or financial variables and do not correlate with other known structural shock measures, including oil, uncertainty, financial, fiscal, and monetary policy shocks.

Given that the EU-ETS only covered a small share of global greenhouse gas emissions and was, over most of the period, the only large-scale emission trading system, it can be ruled out that the carbon policy surprised the price effects in other emission trading systems.

3 Data

3.1 Firm Level Data

The central part of our analysis relies on French firm-level trade data. The French customs collects the data and makes it available at the firm - product - destination/origin level, aggregated to a monthly frequency. To obtain these data, we had to get approval from the Direction Générale des Douanes et des Droits Indirects (DGDDI). The data was then provided through CASD.

It contains information on 578,734 unique firms; however, we restrict the sample to firms that trade for at least two months - this leaves 387,704 distinct firms in the sample. As shown in table 2, the median firm trades with three countries and with six different products. The median firm has been in our sample for almost five years, of which, in one-third of the months, we do not observe any trade. The median monthly value of a firm's product-country trade is 11'000€ while the median is 161'890€. The fact that trade is skewed towards larger firms making larger transactions is a well-known fact. We use a crosswalk provided by Eurostat to get time-consistent CPA 2002 product codes to merge the data with Exiobase.

When working with data on the origin or destination of traded products, we are faced with a specific problem, namely, which country is actually reported as the origin country. For example, if a product is shipped from China to France, it will often enter the EU through Rotterdam or Antwerp. Depending on the data source, this French import from China will now show up as a French import from the Netherlands or Belgium, which would severely limit the usefulness of this data for our purposes. The

Table 2: Descriptive statistics of the trade data

	Median	Mean	Std. Dev.
Months in sample	57	86	79
Months of zero trade	20	41	50
Number of countries	3	6	9
Number of products	6	21	43
Value of trade (per obs)	11'102€	161'890€	3'876'868€

Notes: Summary statistics computed based on our selected sample. The only restriction is that a firm has to trade more than once.

French customs data on imports reports both countries, which allows us to differentiate cleanly between imports from other EU countries and imports from outside the EU. The same does not apply to the export data, where only the first and not the final destination is reported. For example, an export from France to China that goes through the port of Antwerp would be reported as an export to Belgium. As non-EU exports are an integral part of our analysis, this limits what we can do regarding the effect of carbon prices on French Exports. A detailed description of this issue and the data, in general, can be found in Bergounhon et al. (2018)[2].

We supplement the firm-level trade data with balance sheet information, social security data, and an energy consumption survey. The Energy survey is available for a subset of manufacturing firms and contains detailed information on their overall energy cost and usage, also divided by the energy source. The balance sheets are available for the universe of French firms for all relevant years (Ficus/Fare). We combine the energy survey and the balance sheets to compute efficiency measures, e.g., energy expenditures per value added. Balance sheet data is available only at a yearly frequency, which, in combination with our empirical design, reduces the variation in the carbon policy surprise that can be exploited considerably.

All these datasets can be linked through a firm identifier (Siren). However, this identifier does not coincide precisely with the definition of a firm that we have in mind, which relies on operational control. Especially in the mid-2010s, several large firms split their operations into different administrative units without actually splitting the firms

[2]We would like to thank Isabel Méjean for making the cleaning code publicly available on her web page

in terms of control. To get a time-consistent firm definition, we follow the approach developed and used by De Ridder et al. (2022) and Burstein et al. (2020), which is based on previous work by Isabel Méjan see, for example, di Giovanni et al. (2014). [3].

3.2 Emissions Data

We use two different data sets to get data on the emission content of trade: Exiobase and Econinvent.

Exiobase 3 provides consistent environmentally extended multi-regional input-output tables for 44 countries and a "rest of the world aggregate." The construction of this database is described in Stadler et al. (2018) and has been widely used in economic research, e.g. by Shapiro (2021). The data covers 200 product groups or 163 sectors. This data has many desired properties. One advantage of this data is the time series character of the data, covering each year from 1995 to 2019. Further, it contains a variety of environmental emissions such as water usage, energy usage, pollutants, and CO_2 emissions per value of production. We will focus on the latter to estimate the carbon content of trade. According to this data, 64% of products-country observations have a higher CO_2 content than when produced in France. We apply a crosswalk provided by Exiobase to get to CPA 2002 codes that can be linked to the customs data. Due to its aggregate nature, one can link all the observations in the customs data to an aggregated product category in Exiobase.

Ecoinvent (v 3.1.9) is a life cycle inventory database. It covers a wide variety of products and contains detailed information on a multitude of pollutant emissions. Here again, we will focus on CO_2 emissions. It has a more specialized scope with regard to products and countries, but it provides us with a very high granularity and emissions per kg of a product. It has a particular focus on products used as intermediates. Currently, we only have access to the most recent version, which does not contain historical data. If a product appears in Ecoinvent, the information is on a very detailed level (six-digit CPA2015). We can match roughly one-third of our trade flows to Ecoinvent products, predominantly in manufacturing (75%) and some in the agricultural sector (10%).

[3] We thank them for kindly providing us with their code.

These two sources are great complements. Exiobase has the advantage of more comprehensive coverage and yearly measures of CO_2 intensities. However, the measure might be too aggregated, and emission intensities are measured relative to the value of goods. Ecoinvent, on the other hand, provides us with the most recent estimates and covers only parts of our sample. However, emissions are measured relative to weight, and the products covered are measured with greater detail.

4 French Macroeconomic Variables and Carbon Policy Shocks

The principal estimates in Känzig (2022) are based on data for the EA-19 countries. First, we want to check how the French economy reacts to these shocks. For this we estimate the following local projection à la Jordà (2005) at the national level:

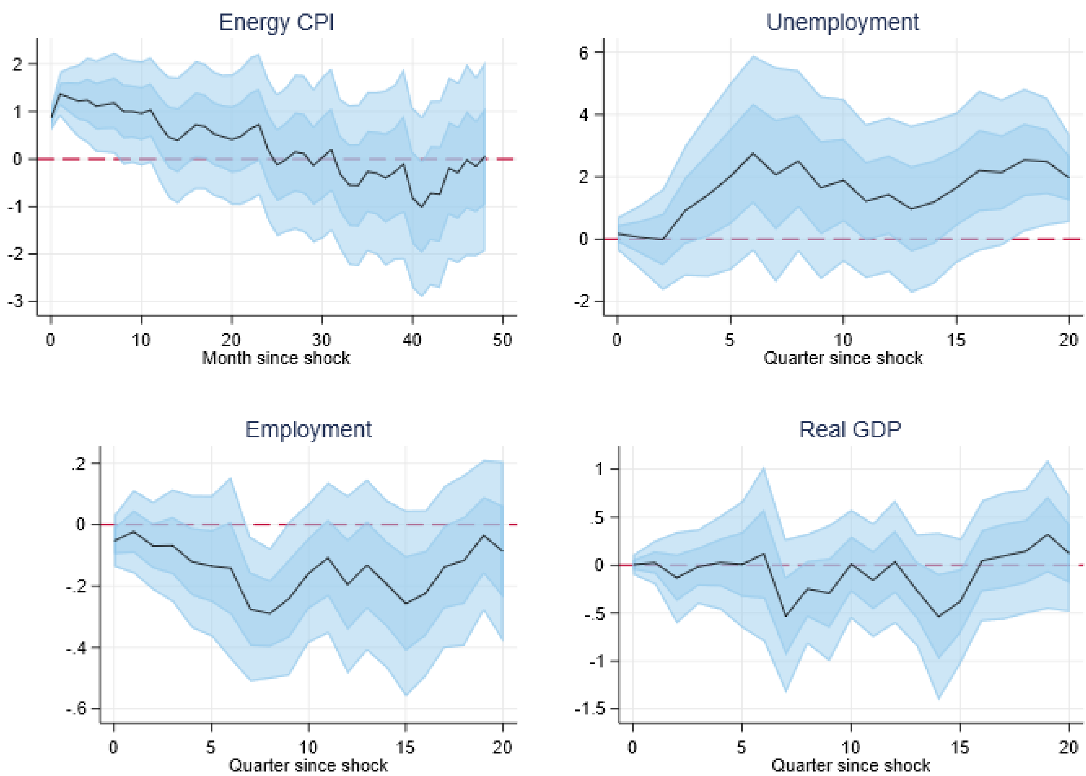
$$y_{t+h} = \alpha_h + \beta_h CPShock_t + \sum_{p=1}^{P} \theta_h^p y_{t-p} + \epsilon_{t+h}, \tag{1}$$

for the quarters $h = 1, ..., 16$. y_{t+h} is the dependent variable at time $t + h$ and $CPShock_t$ are the carbon policy shocks at time t extracted from the Proxy-VAR. In the baseline specification, we include three lags of the dependent variable and we correct for autocorrelation using Newey and West (1987) standard errors.

The main dependent variables are the log of the Energy Consumer Price Index (CPI), the number of unemployed, the number of employed, and real GDP. The coefficient of interest is β_h which captures the response of the dependent variable to a carbon policy shock for each horizon h.

The responses of the dependent variables to a carbon price shock are reported in Figure 1. Following a carbon policy shock that results in a one percent increase of the HICP energy component on impact, all Macro variables react as expected. The shock indeed increases the Energy component CPI by roughly 1 percent, meaning that the response is consistent with Känzig (2022). We also see that real activity is affected. Unemployment takes two quarters to react but is then persistently higher for the remaining 4.5 years. Employment is the mirror image of unemployment, although

Figure 1: The carbon policy surprise series



Notes: The figure plots the response to a carbon policy shock, normalized to increase the HICP energy by 1 percent on impact, for the French Energy CPI (top lef panel), the number of unemployed in France (top right panel), the number of employed people in France (bottom left panel) and the PPI (bottom right panel). The solid lines are the point estimate and the shaded areas are the 95 and 68 percent confidence bands, respectively.

slightly more noisy. Real GDP decreases after one and a half years and tends to be lower for the next two years. However, this effect is not significant.

While the Energy Component of the CPI only reacts for about five quarters before moving back to its original level, that does not mean that the price propagation of the shock through the overall economy is completed. Hensel et al. (2023) analyze how the shock impacts inflation expectations and pricing decisions. Using survey data of manufacturing firms, they show that firms keep adjusting their prices up to 4 years after the shock.

5 Empirical Methodology

We have shown that aggregate measures of economic activity react following a carbon policy shock. We now shift our focus from macro- to firm-level variables.

We estimate the average firm-level response to a carbon policy shock following the approach used by Jordà (2005):

$$log(y^{i,c}_{t+h}) = \beta_h CPShock_t + \omega_h CPShock_t * ETS_c + \alpha^{i,c}_h + \sigma_{y,m} + \sum_{p=1}^{4} \theta^p_h X^i_{t-p} + \varepsilon^{i,c}_{t,h} \quad (2)$$

for horizon $h = 1, ..., 48$. $log(y^{i,c}_{t+h})$ is the dependent variable, e.g., six months ahead trade volume with country c, of firm i at time $t + h$ after the shock. ETS_c is a dummy equal to 1 if the respective country is a member of the EU-ETS and zero otherwise. β_h captures the effect of the carbon policy shock on trade. In contrast, ω_h captures how trade with a country that is also subject to the shock is affected differently. $\alpha^{i,c}_h$ are Firm-country-fixed-effects, $\sigma_{y,m}$ are year and month-fixed effects are X^i_{t-p} are time-varying firm characteristics (e.g. lagged imports). Finally, standard errors are two-way clustered at date and firm level. The coefficients of interest in this case are β_h and ω_h. In this specification, β_h can be interpreted as the reaction of non-ETS trade while the coefficient ω_h reports how ETS trade is affected differently. Therefore, the sum of β_h and ω_h reports the reaction of ETS-trade. The key to our identifying assumption is that the shocks, residuals to a proxy VAR, are uncorrelated to the error term. The shocks are normalized such that the coefficients reflect the reaction of trade to an increase in energy prices of 1% due to an increase in carbon prices. The estimates of this specification correspond to the intensive margin of firms' trading decisions. As outlined earlier, a firm needs to trade at least twice to show up in our sample

As a first step, we analyze the response measured in terms of trade value. French administrative trade data reports the trade flows of each firm at the product/country level at a monthly frequency. The high frequency of the data and the long panel structure make it an ideal setting to study how firms' trading decisions are affected by changes in carbon price. One issue with this level of granularity is that most firms do not trade every month, and the frequency of zero trade flows in the original data. To reduce this kind of noise in our data, we define the log of the cumulative trade of the next six months as the dependent value of the value regressions. However, the frequency of our data and the impulse response function stays on a monthly level. While this increases the precision of our estimates, the point estimates without the six-month aggregations are qualitatively and quantitatively very similar.

In the second step, we aim to understand how the overall CO_2 emissions embedded in these trade flows react. For this purpose, we combine the product/country level trade data with the corresponding average CO_2 intensity from either Exiobase or Ecoinvent. We then aggregate them to obtain the overall CO_2 emissions embedded in all imports of a given firm in a given month. To avoid the problems with zeros mentioned in the prior paragraph, we apply the same procedures. We aggregate our measure of CO_2 embedded in trade over a six-month horizon and use this as a dependent variable in equation (2).

To shed light on potential channels of heterogeneity and as a robustness check, we divide the sample by product classification. On a product-level, we divide the sample by two-digit CPA2015 codes, e.g., Paper and Paper products, Chemicals and chemical products, or Basic pharmaceutical products and pharmaceutical preparations.

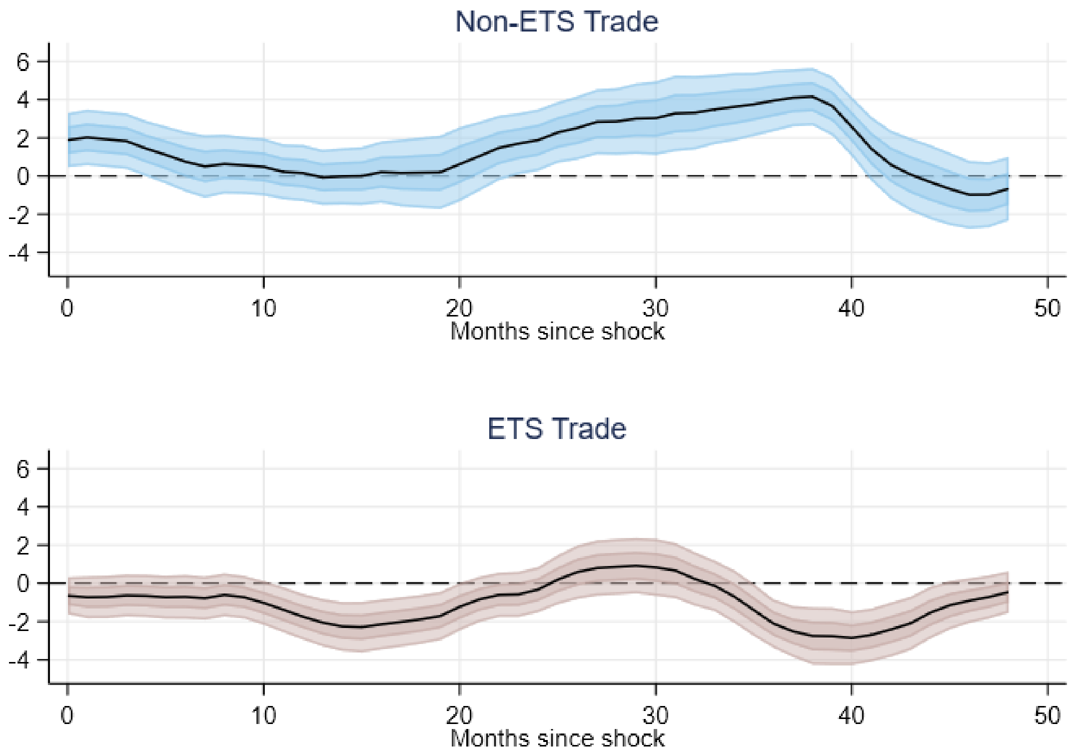
As mentioned in section 2, several measures were implemented to limit carbon leakage in particularly exposed sectors. We investigate how these measures affected carbon leakage by including a dummy for these industries/industries and interacting it with the shock and the ETS dummy, including all possible combinations. We report the results from these regressions in section 6.2.

6 Results

6.1 Trade

We represent the baseline results of regression 2 with the value of trade as a dependent variable in Graph 2. The graphs can be interpreted as impulse response functions and report how trade reacts up to 48 months after the shock. The graph shows how trade reacts after an increase in energy prices of 1% due to an increase in carbon prices. The first graph reports the coefficients β_h in equation 2 and reports the response of

Figure 2: Effects on trade



Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is a 6-month moving average of the total value of trade. We include firm-country, year and month fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm and date level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. Non-ETS Trade: β_h; ETS Trade: $\beta_h + \omega_h$;

imports from countries not participating in the EU-ETS. The results establish both a statistically and economically significant increase in imports in the medium term as a consequence of the shock. However, this increase is only temporary and fades out in the long run. Strikingly, this increase in non-ETS imports is not mirrored similarly by ETS country imports. They are also statistically different from each other. The fact that non-ETS imports increase while ETS imports mainly stay flat is striking evidence for Carbon Leakage. Firms disproportionally shift towards imports that are not priced under the EU-ETS.

We can learn more about the nature of the shock and the adjustment process within firms by looking closer at the time profile of the response. In the first months after a carbon price surprise, there is very little movement in trade. This delay in the response of trade can have several reasons. For one, trade deals are often concluded ahead of time, and production and delivery times can add to these delays. Further sourcing new suppliers either with higher capacity or for new products takes time and usually involves some fixed costs. After about 20 months, firms started to import significantly more products from countries outside the EU-ETS domain. These results are in strong support for the carbon leakage hypothesis. However, over time, the effect of a carbon policy surprise on the value of trade reverts back to zero, which means that in the longer run, there is no sign of carbon leakage. We will show that these results are also accompanied by an increase in CO_2 embedded in imports in the next section.

The coefficients also highlight the economic significance of our findings. To put the results into perspective, non-ETS trade 30 months after the shock is about 3.5% higher than otherwise. This signals that companies in the medium run are very responsive to changes in CO_2 prices. The declining impact on trade is consistent with theories arguing that firms adjust to the higher carbon prices over time. For example, Muûls et al. (2022) argues that firms are inattentive concerning the return on investment in green technologies. Increasing carbon prices then incentivizes investments with positive returns. Another potential channel is that firms overestimate the persistence of the shock. Hensel et al. (2023) show this is the case for price expectations. Känzig (2022) shows that patenting of low-carbon technologies increases after the shock, leading to greater availability of green technologies. The zero effect on trade, in the long run, is consistent with the previous findings in the literature that do not find permanent or only small carbon leakage in the EU-ETS.

We next turn to a subsample analysis and split the import data by product categories. However, interesting patterns emerge on the product level. A sector that was a prime example in the literature of carbon leakage is paper and paper products (see, e.g., paper Aichele and Felbermayr, 2015), as these products also tend to be very carbon-intensive. Indeed, our findings support that carbon leakage in this product group tends to be stronger than in the baseline of all products. Furthermore, the response in ETS vs. non-ETS trade is more pronounced, too. Similar results can be found for chemicals and chemical products. Products where the response is notably muted or statistically insignificant are, for example, basic pharmaceutical products and pharmaceutical preparations. This pattern would suggest that product groups with higher CO_2 intensity show stronger reactions. However, overall, there seems to be no pattern that CO_2 intense products react more strongly, as we will point out in the next section. We refer to the Appendix for the graphs corresponding to the product level analysis.

6.2 Exemptions

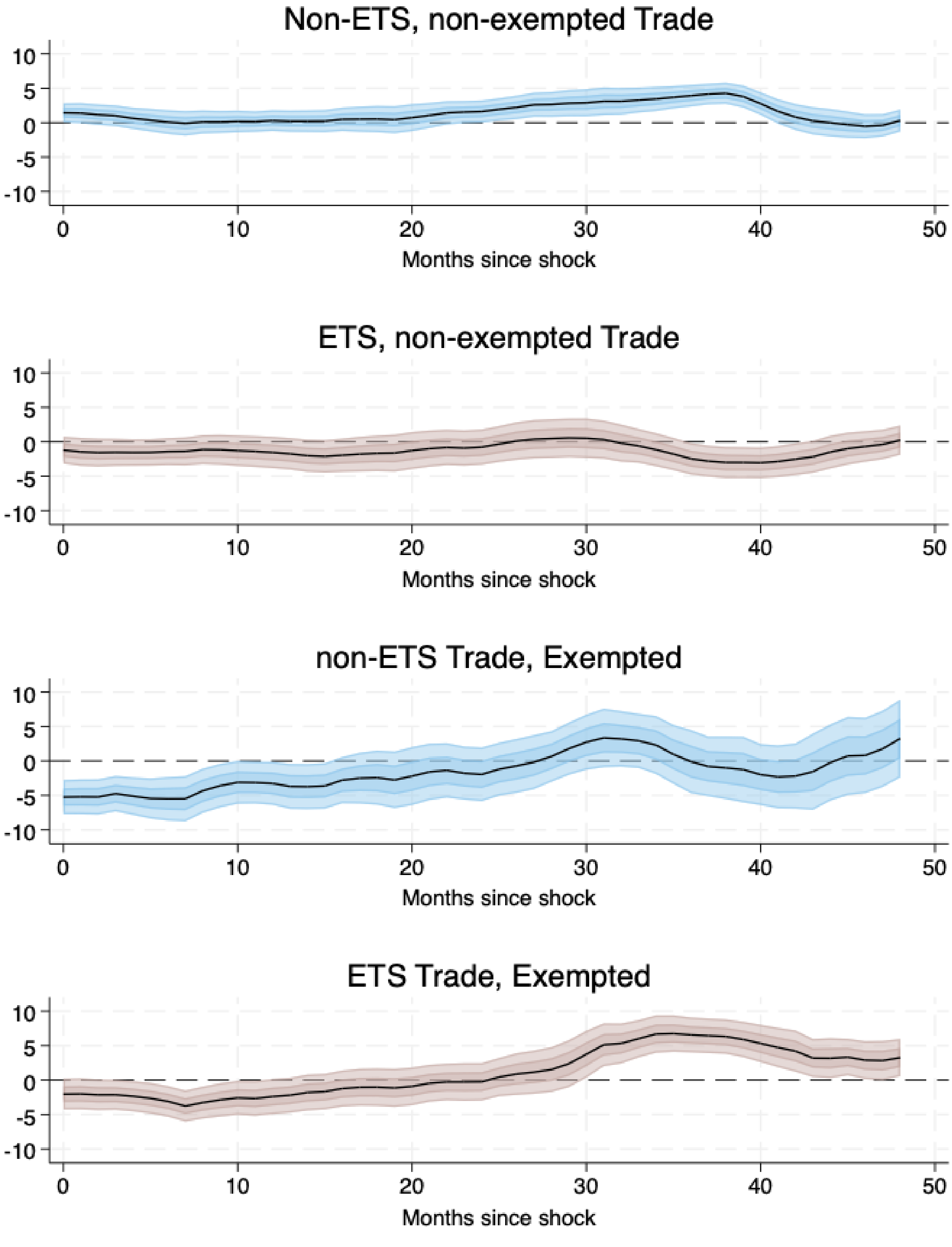
In section 2, we described how carbon leakage was a primary concern when designing the EU-ETS and that measures were put in place to protect industries at high risk of carbon leakage. The core measure is to provide these 154, 4-digit industries with free emission allowances (up to 100%). In this section, we are investigating how these measures affect carbon leakage. To do so, we estimate the following regression at the firm level.

$$
\begin{aligned}
log(y^{i,c,p}_{t+h}) = {} & \beta_h CPShock_t + \omega_h CPShock_t * ETS_c + \\
& + \lambda_h EX^p_t * CPShock_t + \theta_h EX^p_t * CPShock_t * ETS_c \\
& + \alpha^{i,c,p}_h + \sigma_{y,m} + \sum_{p=1}^{4} \theta^p_h X^i_{t-p} + \varepsilon^{i,c}_{t,h} \quad (3)
\end{aligned}
$$

for horizon $h = 1, ..., 48$, country c, at time t of firm i for products that are deemed at risk of carbon leakage p. The dummy EX takes the value one if the product is deemed to be at risk of carbon leakage by the EU Commission. $log(y^{i,c}_{t+h})$ is the dependent variable, e.g., six months ahead of trade volume. β_h captures the effect the carbon policy shock has on trade. ω_h captures how trade with a country that is also subject to the shock is affected differently. λ_h captures how trade is affected differently if it is on the carbon leakage risk list, and ω_h captures how trade with ETS countries is affected differently if it is on the carbon leakage risk list [4]. For the reader's ease, we will report the absolute effects of the shock and leave the differential impacts in the appendix.

[4] As a reminder for the reader: $\alpha^{i,c}_h$ are Firm-country-fixed-effects, $\sigma_{y,m}$ are year and quarter-fixed effects are X^i_{t-p} are time-varying firm characteristics (e.g. lagged imports). Standard errors are two-way clustered on date and firm level.

Figure 3: Trade patterns comparing exempt and non exempt products



Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is a 6-month moving average of the total value of trade. We include firm-country-exemption, year and month fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm and date level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. Non-ETS, Non-Exempted Trade: β_h; ETS, Non-Exempted Trade: $\beta_h + \omega_h$; Non-ETS, Exempted Trade: $\beta_h + \lambda_h$; ETS, Exempted Trade: $\beta_h + \omega_h + \lambda_h + \theta_h$;

The rationale behind this specification is to identify those products that would potentially qualify for special treatment, such as free emission allowances, if they were produced in the EU-ETS domain and to check whether importing these goods from outside the EU-ETS behaves differently after the carbon price shock. While the allocation of free allowances does not change incentives, i.e., marginal costs of production, it decreases overall costs, increases overall profits, and therefore reduces the need to raise prices if international competition would make it hard to do so, at least in the short run. Most importantly, the latter mechanism is a specific reason for an industry or product to be included on the EU Commission's exemption list.

We depict the result of this regression with trade value as the dependent variable in Figure 3. Trade with non-exempted products reacts in the same way as aggregate trade. Trade within the EU-ETS is not significantly affected by the carbon price shock. Trade with non-ETS countries picks up after 18 months and remains elevated for the next two years, leading to significant carbon leakage during that time.

We show the impact of the carbon price shock on goods at significant risk of carbon leakage in the bottom two panels of Figure 3. Trade in these goods with non-ETS countries is less affected than other goods. We do not see the same increase after 18 months in non-exempt goods. The results are even more striking as trade competition is a key reason to be on the exemption list, and one would expect an even stronger result than for other goods.

The trade reaction with exempted goods within the EU-ETS shows an interesting pattern. We find that trade picks up similarly to trade in non-exempted goods with non-ETS countries, although the response is slightly delayed.

It seems that the measures are successful in protecting industries at risk from carbon leakage from competition from outside the EU-ETS. However, there is a particular reallocation within the EU-ETS away from French firms. As long as this reallocation is towards more efficient firms, this might be the ideal scenario for the European Union.

6.3 Carbon Leakage

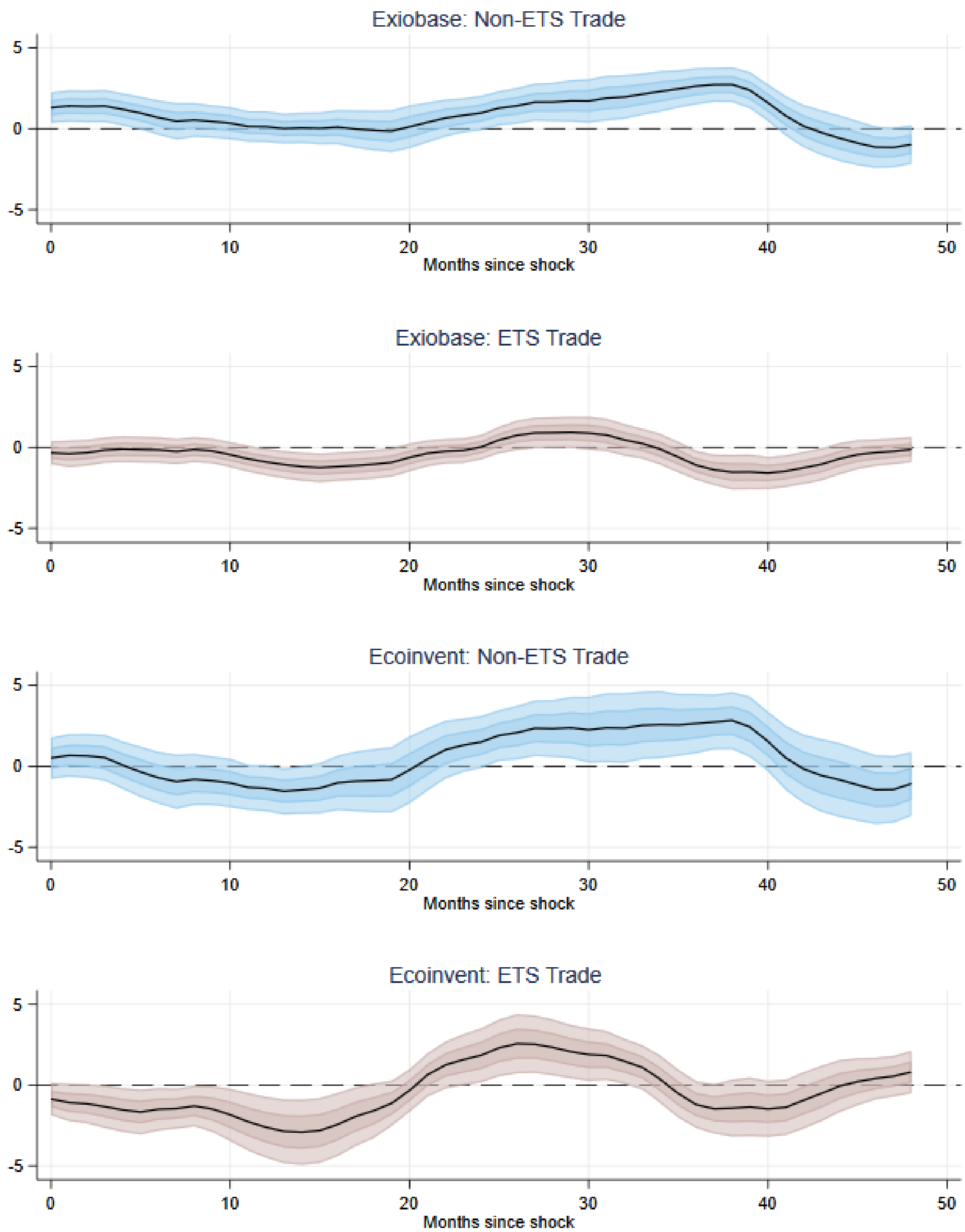
In this section, we focus on the embedded emissions, the dependent variable now being total emissions embedded in trade. We use information on emissions from two different databases, Exiobase and Ecoinvent. For this, we merge the product level data with the corresponding level in CO2 emission from these databases. Exiobase measures CO2 emissions embedded in value, so we multiply the trade value in our data with the CO2 measure provided to get the total CO2 content. Ecoinvent provides the CO2 content by kilogram, and therefore, we multiply the weight measure in our data with the CO2 measure provided by Ecoinvent. These measures are then aggregated on a firm and month level to get total CO2 emissions embedded in import for each firm and month.

In the top two panels of Figure 4, we use emissions data coming from Exiobase. The time profile is very closely aligned with the response of trade value. In the first periods, embedded emissions in trade do not react significantly. It is only over time that emissions from trade with non-ETS countries start increasing. The peak is reached after approximately three years when emissions embedded in trade with non-ETS countries are up to 2.6% higher than they would have been without the shock. After that, embedded emissions start decreasing again until they reach the level that would have been preserved without the shock.

In the bottom two panels of Figure 4, we plot the coefficients using emissions data from Ecoinvent. We have discussed the advantages and disadvantages of both emissions datasets extensively in section 3. It is comforting to know that our results are robust to the choice of emissions data. In particular, Exiobase is based on transaction value, while Ecoinvent is based on transaction volume, which is, for instance, independent of any price or exchange rate movements. The time profile remains qualitatively the same, and the magnitudes coincide quantitatively. Any difference in timing might be due to the sample that changes between the datasets, with Ecoinvent having smaller coverage than Exiobase.

One important channel for the muted CO_2 response is the EU Commission's exemption list. Products on this exemption list are carbon intensive. In the previous section, we highlighted that the exemptions are successful in preventing carbon leakage, and the products that do respond and that are not on the list are less carbon intense. We replicate the exemption regression using CO2 from Exiobase as the dependent variable

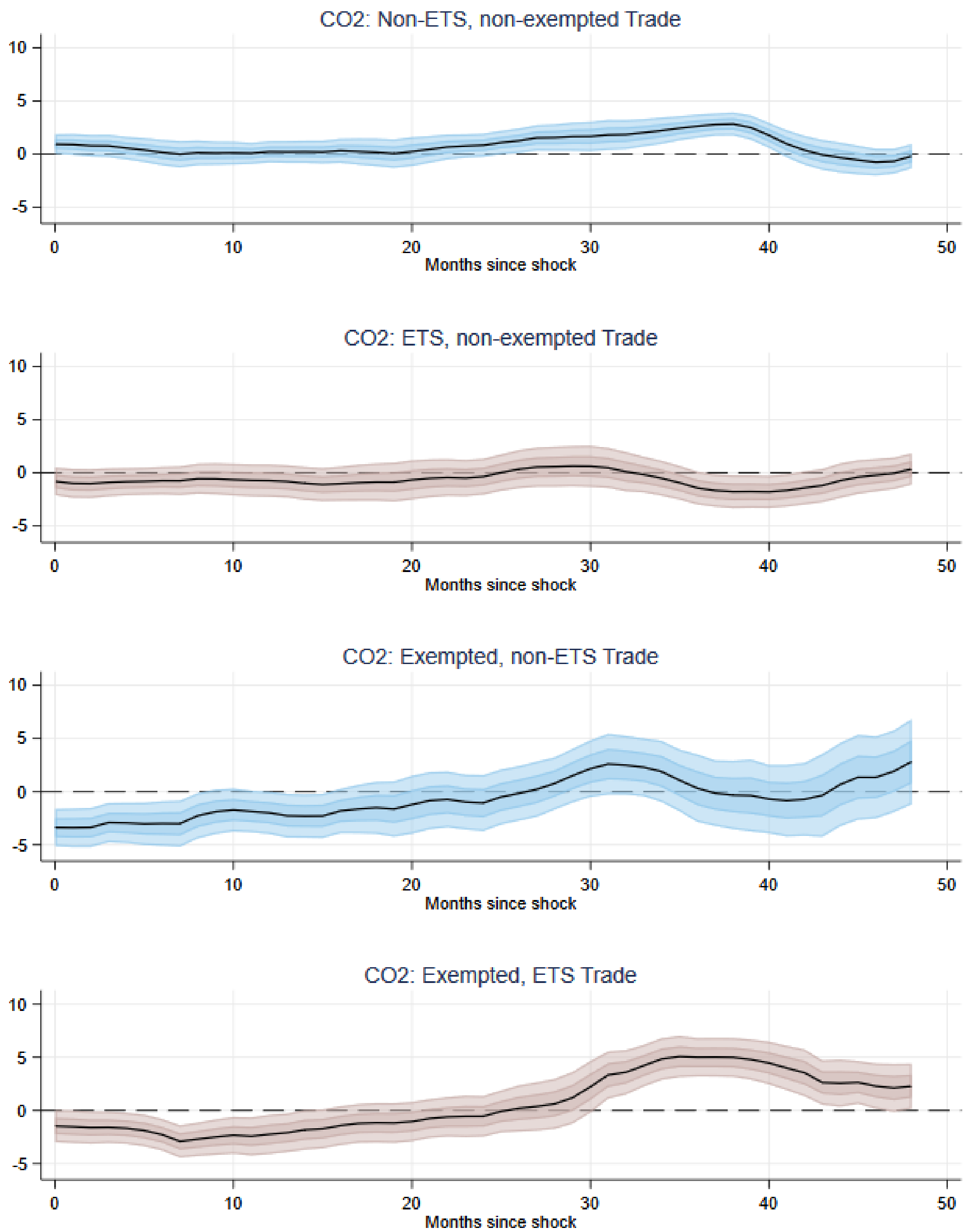
Figure 4: Carbon leakage



Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is a 6-month moving average of the quantity of trade multiplied with average co2 content for the respective product. In the upper two panels we use information on CO2 content from Exiobase while in the lower two panels we use information from Ecoinvent. We include firm-country, year and month fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm and date level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. Trade data underlying this graph comes from the customs data, emissions data comes from ecoinvent. Non-ETS Trade: β_h; ETS Trade: $\beta_h + \omega_h$;

in 5, confirming a similar pattern as before. The CO2 intensive goods on the exemption list also do not react to imported CO2 content.

Figure 5: Carbon leakage comparing exempt and non exempt products



Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is a 6-month moving average of the value of trade multiplied with average co2 content for the respective product. We include firm-country-exemption, year and month fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm and date level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. Trade data underlying this graph comes from the customs data, emissions data comes from Exiobase 3. Non-ETS, Non-Exempted Trade: β_h; ETS, Non-Exempted Trade: $\beta_h + \omega_h$; Non-ETS, Exempted Trade: $\beta_h + \lambda_h$; ETS, Exempted Trade: $\beta_h + \omega_h + \lambda_h + \theta_h$;

6.4 Discussion

In this section, we discuss the interpretation of our estimates. Generally, our identification strategy allows us to estimate the effects of marginally changing carbon policies and the resulting CO_2 price changes. Therefore, we do not capture the impact of introducing a CO_2 price. This is an important distinction: When a CO_2 price is implemented, firms form their expectation about long-term price developments, make long-term investment decisions abroad, and start looking for new suppliers abroad. The introduction is a rather significant shift compared to a regime where no carbon prices exist. It can trigger events that justify considerable fixed costs, such as reallocating production abroad or sourcing from a new country. We show that even marginal changes in carbon policies can have consequences for trade flows, and in light of this, our estimates of carbon leakage should be treated as a lower bound.

Further, our results show a considerable time delay concerning the trade response, and the effect peaks only 30-40 months after the shock. There are several reasons to rationalize this. First, timing frictions are naturally embedded in international trade, such as ordering, production, and shipping time. It also takes time for the supplier abroad to expand their production. Another important factor is price stickiness. The general CPI energy components react quickly on impact of the policy surprise and only in the short to medium term (see Figure 1). Hensel et al. (2023) show that the general shock propagation to firm prices takes longer as prices are sticky, and therefore, it takes a considerable amount of time for price increases to cascade through the supply chain. Firms increase their prices for up to 13 quarters, which is consistent with the timeline of our trade estimates.

But how can one rationalize the missing long-term effect? An optimistic scenario is that in reaction to a carbon price surprise, the economy starts to adapt, and within a five-year window after the shock, production technology becomes more efficient, leading to a phasing out of the shock in the long run. There is relatively robust evidence that innovation activity increases and would be in line with Muûls et al. (2022). Also, Känzig (2022) establishes that patenting activity increases in reaction to a carbon shock. We provide further evidence for adaption on the firm level. In Figure 6, we show that firms increase their energy efficiency; in particular, they increase their revenue per unit of

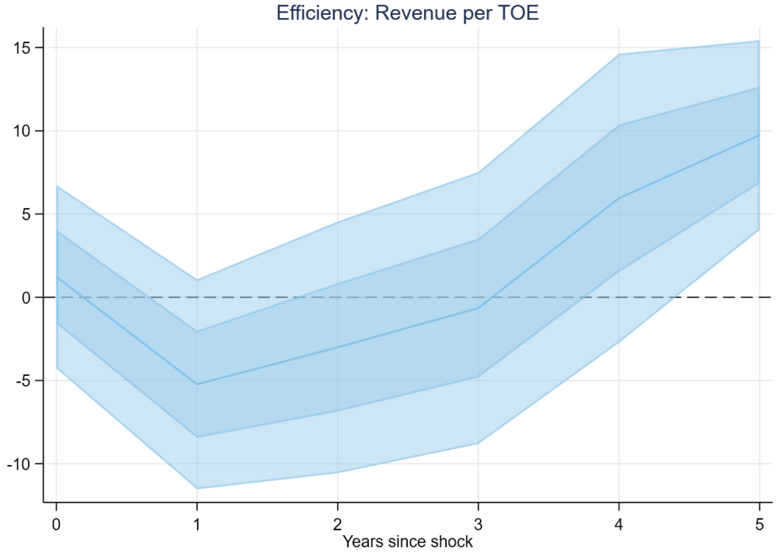


Figure 6: Revenue per tonne of oil equivalent (toe)

Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is the log of the revenue generated relative to energy used in tonnes of oil equivalent (TOE). We include firm fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. trade data underlying this graph comes from balance sheets (FICUS/FARE) and the energy consumption survey.

energy used five years after the shock. We can establish that this increase cannot be due to import substitution as the import levels have already reached pre-shock levels.

A more neutral explanation for the lack of permanent effects lies in the nature of our identification strategy and measuring the impact of marginal changes in an existing carbon price. After a carbon price is introduced, firms form their expectation about the future price trajectory. Our shock captures a short-term deviation from this price path but does not impose that firm price expectations, in the long run, are changed or wrong. In the long run, prices again come closer to the original projection, and the firm only needs to adjust its short-term behavior.

We next discuss potential reasons why the response in CO_2 emissions embedded in imports is smaller in magnitude than the response in trade value. One channel that was already outlined is the exemption list of the EU Commission, which contains measures such as the free allocation of emission certificates for sectors that are carbon/energy intensive and tradeable. Our empirical results show that, indeed, imports of these products behave differently. Further, a more general point regarding our estimates is that they capture the overall response in trade to a carbon policy surprise. An important determinant will be the trade elasticity of a sector/product. An important factor for this is how easy it is to substitute for imports from abroad. This is a further layer that has to be taken into account and could explain why there is no stronger reaction for carbon/energy-intensive goods.

7 Conclusion

Global coordination for a uniform carbon has been unsuccessful, and as a first step, unilateral carbon pricing policies have been put in place in some regions. However, such a price does not reach its full potential if it can be avoided by buying products from abroad. We study the risk of carbon leakage in the context of the EU-ETS. This carbon price, like most other carbon prices around the world, is incomplete as it does not have a carbon border adjustment mechanism (yet). Using French firm-level trade data and carbon policy surprises developed in Känzig (2022), we show that a carbon policy surprise increases trade with countries that do not participate in the EU-ETS in the medium term. In contrast, trade with ETS member countries is unaffected or even decreases. However, in the long run, trade volumes converge back to pre-shock levels. We show that the response in trade volume is also mirrored by CO_2 emissions embedded in these import flows. Interestingly, this increase is weaker, suggesting that less CO_2-intense products drive the trade response. The European Union defined certain industries and products as at significant risk of carbon leakage and implemented measures to protect them, i.e., allocation of free emission certificates. We outline that the response to a carbon policy shock of these products differs significantly. Imports from non-ETS countries do not increase for products identified as being at risk of carbon leakage and potentially subject to these measures. This is strong evidence that the measures actually helped attenuate carbon leakage.

We discuss potential mechanisms and caveats. Our estimate delivers a measure for the intensive margin of firms' trading decisions. In the past, several studies on the EU-ETS found no or only a little carbon leakage. Our approach sheds light on a potential explanation, namely that carbon leakage is only temporary and general equilibrium effects, e.g., energy prices are important. Regarding policy measures, we show particular policies targeting products and sectors at risk of carbon leakage that seem to be effective at preventing import substitution and, consequently, carbon leakage. However, these results can still come at a high fiscal cost and hinder the transition towards a greener economy. Our results highlight the challenges when implementing an Emissions Trading System. It must be designed carefully with the threat of carbon leakage in mind. A carbon border adjustment mechanism could deal with this more effectively, but future research is needed once these policies are in place.

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A Additional information

A.1 Construction of shocks

The measurement of the surprise series, although very clever, is imperfect. There will be some measurement error, for example, because not all relevant events have been identified, or the window around the announcement has to be relatively wide (1 Day Känzig (2022)). Hence, following Stock and Watson (2018), the surprise series is used as an external instrument in structural VAR. In this section, we will briefly outline the approach that was performed by Känzig (2022) to arrive at the shock series, but it is central to the understanding of our paper.

We use the standard notation in the VAR literature. As a quick reminder: vectors and matrices are denoted in bold, e.g. $\boldsymbol{y}_{t-p}$ where the subscript t denotes the year and p denotes the lag of a variable. Individual elements are written as $y_{i,t}$, where i denotes the row. $\boldsymbol{y}_t$ denotes the $n \times 1$ vector of endogenous variables and $\boldsymbol{B}_1$ to $\boldsymbol{B}_p$ are coefficient matrices of size $n \times n$. $\boldsymbol{u}_t$ is the $n \times 1$ vector of reduced form innovations and $Var(\boldsymbol{u}_t) = \Sigma$.

A standard VAR model takes the following form

$$\boldsymbol{y}_t = \boldsymbol{B}_0 + \boldsymbol{B}_1 \boldsymbol{y}_{t-1} + ... + \boldsymbol{B}_p + \boldsymbol{y}_{t-p} + \boldsymbol{u}_t \tag{4}$$

Under the assumption that the VAR is invertible, $\boldsymbol{u}_t$ can be defined as

$$\boldsymbol{u}_t = \boldsymbol{S}\boldsymbol{\epsilon}_t \tag{5}$$

Where $\boldsymbol{S}$ is an $n \times n$ non-singular matrix. The structural shocks $\boldsymbol{\epsilon}_t$ are assumed to be serially and mutually uncorrelated. Without loss of generality we order our shock of interest first in $\boldsymbol{\epsilon}_t$, thus it is denoted as ϵ_{1_t}. The scales of $\boldsymbol{\epsilon}_{1,t}$ and $\boldsymbol{S}$ are not separately identified. It thus makes sense to scale such that they have a meaningful economic interpretation. In our case, they are scaled such that a one unit increase in ϵ_{1_t} increases household energy prices by 1%.

To be used as an external instrument z_t, our surprise series is required to be relevant, thus being correlated with the underlying structural shock of interest and exogenous, in other words, uncorrelated with other shocks in the model Montiel Olea et al. (2018). Thes conditions can be written as

$$\mathbb{E}[z_t \epsilon_{1,t}] = \alpha \neq 0 \tag{6}$$

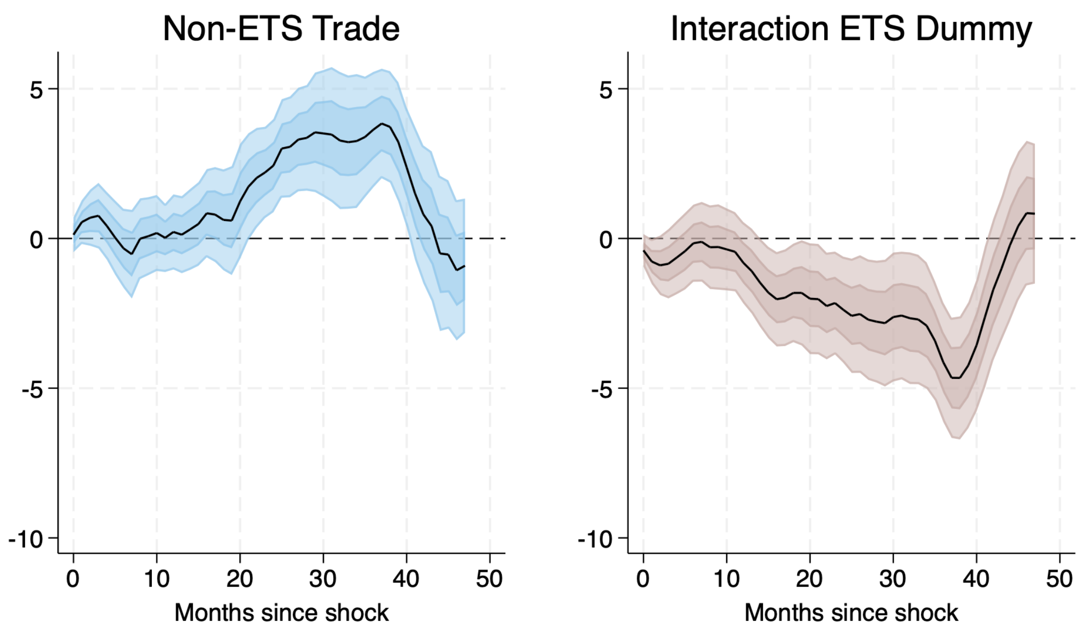
$$\mathbb{E}[z_t \epsilon_{j,t}] = 0 \text{ for } j \neq 1 \tag{7}$$

Using these assumptions the instrument can be used to recover the structural shock of interest $\epsilon_{1,t}$ [5].

[5]See Stock and Watson (2018) page 4 for the derrivation

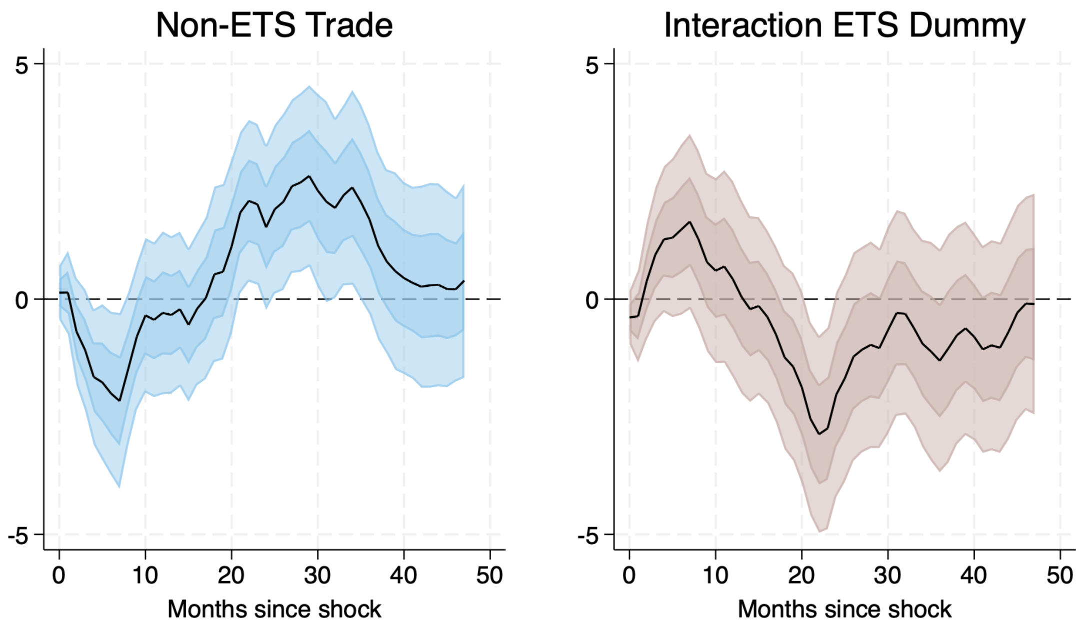
B Additional figures and tables

Figure 7: Effects on trade: Paper and paper products



Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is a 6-month moving average of the total value of trade. The sample is restricted to products classified Paper and paper products (CPA2015:17). We include firm-country, year and month fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm and date level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. Non-ETS Trade: β_h; Interaction ETS Dummy: ω_h;

Figure 8: Effects on trade: Basic pharmaceutical products and pharmaceutical preparations



Notes: This figure displays the average firm response to a carbon price shock that increases energy prices by 1%. The dependent variable is a 6-month moving average of the total value of trade. The sample is restricted to products classified Basic pharmaceutical products and pharmaceutical preparations (CPA2015:21). We include firm-country, year and month fixed effects and control for 4 lags of the dependent variable. Standard errors are clustered at the firm and date level. The solid lines are the point estimates, and the shaded areas are the 95 and 68 percent confidence bands, respectively. Non-ETS Trade: β_h; Interaction ETS Dummy: ω_h;