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How the three Ds affect firm pricing, markups and productivity

The effects of carbon pricing along the production network

by Ralf Martin, Mirabelle Muûls and Thomas Stoerk

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Editorial

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The effects of carbon pricing along the production network*

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Abstract

Carbon markets are a central instrument to decarbonise our economies and mitigate the impacts of climate change. Within the European Union, carbon pricing to date has primarily targeted electricity generation and greenhouse gas-intensive industries, and regulatory focus has typically been confined to a subset of firms. This paper explores how the carbon price confronting regulated firms not only shapes their own operations and investment choices but also exerts influence on other entities within their customer and supplier network, even in the absence of direct carbon pricing of these suppliers or clients. Such influence could manifest through alterations in production processes, products and prices, market structures and innovation. Leveraging a distinctive dataset for Belgium, this research investigates the impact of the EU's carbon price on low-carbon innovation, supply-chain dynamics, and energy economic activity throughout the Belgian economy's production network.

Keywords: Emissions pricing, production network, clean innovation.

JEL codes: Q58, Q55, L14, H23, F18.

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1 Introduction

What are the effects of carbon pricing? A large literature has estimated the impacts on regulated firms directly, with a specific focus on industrial firms. There are, however, potential effects of carbon pricing that can be felt along the entire production network that makes up an economy. For example, downstream buyers of intermediates produced by firms subject to carbon pricing could be affected by this carbon price through changes to their inputs costs. Similarly, a firm that sells intermediates to a firm subject to carbon pricing might see a change in the demand for its products.

A large literature has shown production network effects to be crucial for the quantitative analysis of economic phenomena such as aggregate fluctuations (Acemoglu et al., 2012), growth in economic activity (McNerney et al., 2022, Baqaee et al., 2023), productivity (Bernard et al., 2022, Amiti et al., 2023) or trade (Dhyne et al., 2021). However, to date, no evidence exists about the impacts of carbon pricing along the production network. This is despite the fact that recent theoretical contributions suggest that such effects could be of central importance to design more effective carbon markets (King, Tarbush and Teytelboym, 2019).

Our study uses confidential and anonymised microdata featuring the population of Belgian firms. Based on Belgian VAT-incurring transactions, we construct the entire domestic production network for the Belgian economy. Belgium is a key industrial country in Europe, which has been part of the EU's carbon market, the European Union Emissions Trading System (EU ETS) since a carbon price was established in 2005. Our sample spans years from 2013-2022.

We start by documenting a number of new stylized facts about the reach of carbon pricing in the EU. First, we show that there is in a quantitatively important indirect coverage of the EU ETS: many firms that are not themselves directly regulated by the EU ETS have economically important downstream or upstream links to firms that are regulated. Second, we find a large heterogeneity across industrial subsectors in the ratio of indirect to direct links. "29 Motor Vehicles" or "28 Machinery", for instance, contain only a limited number of companies directly regulated by the EU ETS, but indirect links are present for as many as 40% of firms in these sectors, in particular on the client side. Third, we document that firms regulated under the EU ETS are less likely to acquire new clients and to acquire new suppliers than other firms.

In a second part, we identify the causal effect of being subject to a carbon price on regulated firms, on firms upstream of regulated firms, and on firms downstream of regulated firms. Relying on a shift-share approach that takes into account the differential exposure of a firm's activity to the carbon price, we analyse the impact on firm-level economic outcomes - value-added, employment and investment. Our empirical strategy relies on the sharp increase in the price of an ETS allowance that occurred between 2015 and 2022.

To conclude, we explore how innovation - measured through the filing of patents- is affected by this differential exposure to the carbon price.

The remainder of this paper is organised as follows. Section 2 discusses the policy background and gives context about the past developments of the EU ETS during our sample period, as well as future developments that speak to the relevance of our research. Section 3 highlights our contribution to the existing literature. Section 4 explains our data sources while 5 provides descriptive statistics and shows new stylised facts about the reach of indirect regulation via the EU ETS. Section 6 explains our empirical methodology, and section **??** discusses results and next steps. Section **??** draws preliminary conclusions - given the work-in-progress status of this paper.

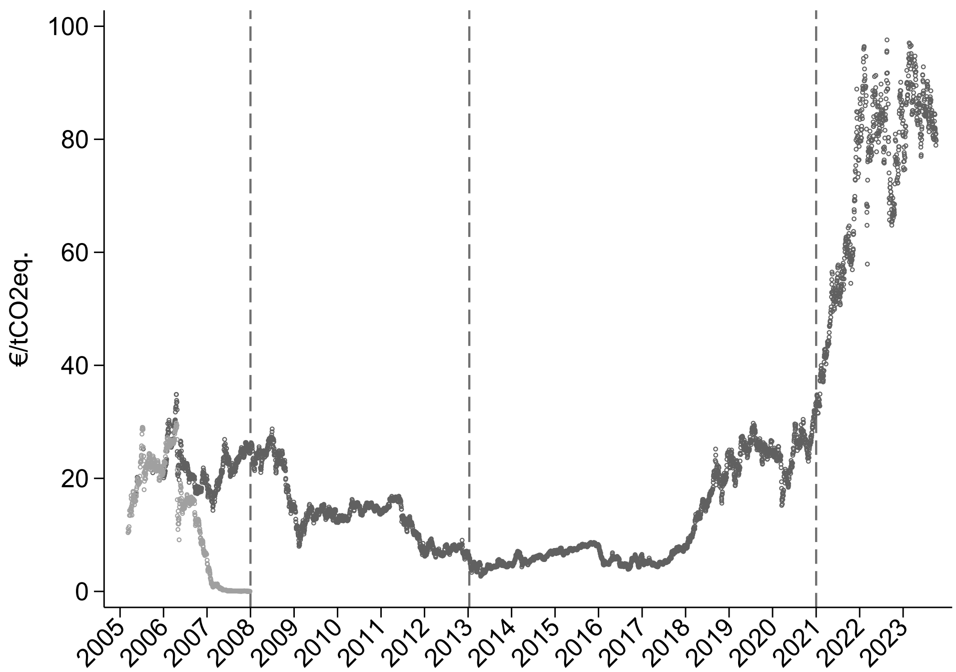
2 Policy Background: the EU Emissions Trading System

The European Union Emissions Trading System (EU ETS) was first launched in 2005. It covers industry and the power sector and - since 2012 - parts of aviation. The functioning of the EU ETS is legally divided into four phases: Phase I (2005-2007) established the EU ETS as the world's biggest carbon market. This first trading period functioned as a pilot phase to incentivise learning-by-doing. Phase II (2008-2012) saw an increase in geographic scope (Iceland, Norway and Liechtenstein joined on 1st January 2008) and sectoral scope (aviation was brought into the EU ETS on 1st January 2012). Phase II was the first fully functioning phase of the EU ETS. Phase III (2013-2020) saw significant additional changes, such as a progressive shift away from grandfathering toward auctioning of allowance. The geographic scope of the EU ETS changed further (with Croatia joining on 1st January 2013, and the UK leaving on 31 December 2020 as a result of Brexit). Crucially, Phase III marked the start of a legally binding declining cap, so that overall greenhouse gas emissions in the EU ETS would have to drop by 1.74% annually. In 2018, Phase III furthermore saw the establishment of the market stability reserve, a mechanism to avoid excessive build-up of banked allowance supplies. In 2021, the EU ETS entered Phase IV. The key structural changes to the EU ETS were a tightening of the cap decline to 2.2% annually, and an updating of allocation benchmarks for free allowances for industry. To date, the EU prices emissions of over 10,000 electricity and heat plants and manufacturing installations, as well as 371 aircraft operators (the latter mostly on domestic routes). In the future, carbon pricing in the EU will expand substantially: as of 2027, a second EU emissions trading system (EU ETS 2) will price greenhouse gas emissions of buildings and road transport. The EU ETS currently prices around 36% of the EU's greenhouse gas emissions. This proportion will raise to around 75% as of 2027.

The carbon price level in the EU ETS deserves particular attention, as it will determine the strength of the treatment in our study. As shown in figure 1, the four distinct phases of the EU ETS have shown four distinct average price levels. In Phase 1, the market first started to experiment with trading, and a price formed. Market participants initially settled on a price of 30€/tCO_2eq., but after the first compliance cycle it become clear that allocation was more generous than initially expected, leading to the market price to drop. Prices stabilised around 20€/tCO_2eq. going into Phase II, but then again dropped to about 15€/tCO_2eq. as a result of the Great Recession, which led to lower demand for emissions allowances than envisaged when the cap was designed. And while the European Commission has always maintained that the key motivation was the cap, it became increasingly clear in Phase III that a carbon price as low as 5€/tCO_2eq. would not be able to drive power sector and industrial decarbonisation in the EU. As a result, several changes to the EU ETS functioning were implemented, most notably the creation of the market stability reserve (MSR) designed to prevent an excessive buildup of banked allowances. The establishment of the MSR in 2018 was followed by a shift in European ambition: up to 2018, climate policy had played only a minor part in the overall economic policy mix of the Union. As of 2018, climate started to take center stage, with the EU's adoption of climate neutrality as target for 2050 (later made legally binding in the European Climate Law), which culminated in the European Green Deal and an ambitious increase in the 2030 greenhouse gas emissions reduction target, which led to a strengthening of all European climate policy instrument, in particular carbon pricing. As a result, the current market price hovers around 80-100€/tCO_2eq.

Prior to 2040, the cap covering industry and the power sector will decline to zero (Pahle et al., 2023). Experts expect this price to rise further as the cap for the EU ETS will approach zero in little more than fifteen years. One of the often used justifications for carbon pricing is that this instrument allows firms to abate that part of their emissions that can be cut at least cost, without the regulator needing to details on individual firms' abatement cost. Now that the EU has decided to cut all greenhouse gas emissions from industry and the power sector, this question transforms to: is there a way to fine-tune carbon market design such

Figure 1: The carbon price in the EU ETS.



Notes: Observations in gray correspond to Phase I spot prices, while observations in black combine Phase I future prices as of 1st January 2006 with observed spot prices from Phase II onwards, thus representing the economically meaningful carbon price in the EU ETS. The vertical dashed lines delimit the four phases of the EU ETS to date. Price data is in nominal €/tCO_2eq.

that the economic cost of full decarbonisation is reduced? In this work, we bring evidence about the reach of carbon pricing in the production network, offering avenues for further policy development aiming to maximise low-carbon innovation and minimising the economic cost of net-zero.

3 Contribution to the existing literature

Empirical evidence on how linkages between firms affect the effects of carbon pricing is still lacking. A growing literature has been using differences-and-differences research designs in combination with matching techniques to analyze the impact of carbon pricing on outcomes of regulated firms, mainly drawing on samples from industry. These studies can be divided into the different outcome variables that have been studied. On whether carbon pricing in the EU ETS reduced firm-level greenhouse gas emissions, the evidence suggests that the answer is nuanced, and dependent on the context. A study based on a sample of French industrial firms through 2012, for instance, finds that firms subject to carbon pricing reduced their greenhouse gas emissions by around 15% (Colmer et al., Forthcoming). Dechezleprêtre, Nachtigall and Venmans (2018) confirm this magnitude, finding emissions reductions of 10% between 2005 and 2012 based on a sample from France, the Netherlands, Norway and the United Kingdom. Klemetsen, Rosendahl and Jakobsen (2020), on the other hand, only find mixed evidence that EU ETS regulation reduced greenhouse gas emissions in a sample of Norwegian manufacturing plants through 2013. Jaraite and Di Maria (2016) similarly find no impact of the EU ETS on firm-level emissions in Lithuania in a sample between 2003 and 2010.

On economic outcomes, the literature has established the robust conclusion that being subject to a carbon price does not lead to adverse economic effects at the firm-level. Dechezleprêtre, Nachtigall and Venmans (2018), for instance, find no significant impact on profits and employment, and an increase in firm revenues and fixed assets for regulated firms. The absence of detrimental effects of firms is confirmed by Löschel, Lutz and Managi (2019), who find that the EU ETS likely improved economic performance of regulated firms. The EU ETS carbon price, lastly, has induced some low-carbon patenting that would not have happened in the absence of carbon pricing (Calel and Dechezleprêtre, 2016, Calel, 2020).

The focus of this literature has so far been to study the effects of carbon pricing only on firms themselves subject to carbon pricing, under the assumption that non-treated firms were unaffected. Only recently has this literature started to explore how market structure interacts with the effects of a carbon price (Fabra and Reguant, 2014, Hintermann et al., 2020, Barrows et al., 2023). This has also been explored in the context of other environmental policies, with a particular focus on intra-firm reallocations (Gibson, 2019, Chen et al., 2021). From a theoretical perspective, the position of a firm in a network has also inspired the definition of optimal carbon pricing as considering the entire production network matters for the costs, benefits, and speed of the policy's effect (King, Tarbush and Teytelboym, 2019). This expands on earlier theoretical work that shows how an upstream supplier of abatement technology can react to regulation on pollution of its downstream buyers (Greaker, 2006, Heyes and Kapur, 2011, Greaker and Midttømme, 2016). Devulder and Lisack (2020) find that a carbon tax in a calibrated production network model affects upstream sectors more than downstream sectors. Aghion et al. (2024) show that taking into account production networks yields important insights into the optimal climate policy instrument mix to induce adoption of decarbonised technology.

Knowledge about the effects of carbon pricing along the production network can therefore translate into insights about which intervention points to use to optimise climate policy design (van der Ploeg and Venables, 2022, Mealy et al., 2023). That such effects could be quantitatively important has been shown by Konc, Savin and van den Bergh (2021), who ask how optimal carbon tax design differs when consumers are subject to indirect social effects. In their calibration, these indirect influences allow the carbon tax required to achieve a given emissions target to be reduced by 38%. Moreover, taking into account firm centrality in carbon market design could help reduce the bureaucratic burden to regulated companies, which has been documented for existing carbon markets (Kurz, 2024).

Empirical evidence on the indirect effects of carbon pricing along the production network, however, is still scarce. The empirical ex-post literature has only recently started to look into the effects of climate policy along production networks. Cahen-Fourot et al. (2021), for instance, develop a new methodology to estimate value changes for capital stocks at risk of becoming stranded as a consequence of a decarbonisation policies on inputs, while Dechezleprêtre and Kruse (2022) rely on input-output tables to associate a measure of climate policy stringency with economic outcomes at the sectoral and firm levels. Closely related to this paper is Miller (2015), who uses dynamic count models to relate carbon pricing to low-carbon innovation in both regulated and unregulated firms. He finds the indirect innovation effects of carbon pricing to be of the same order of magnitude of the direct innovation effects[1]. This first result confirms the theoretical insights that indirect effects of climate policies could be quantitatively important[2].

Our work also relates to production network-based research on topics in productivity, macroeconomics and trade. The crucial importance of production networks in the analysis of economic phenomena such as aggregate and sectoral fluctuations (Acemoglu et al., 2012, Leng et al., 2024), growth in economic activity (McNerney et al., 2022, Baqaee et al., 2023) and productivity (Bernard et al., 2022, Amiti et al., 2023) and trade (Dhyne et al., 2021), is well established[3]. The aforementioned empirical insights from this literature have shown production networks to be crucial for both understanding and quantification, which has led to calls for the need to provide global production network data as a public good needed to

[1] An earlier tentative exercise to gauge indirect effects of the EU ETS on low-carbon patenting is contained in a robustness check in Calel and Dechezleprêtre (2016). Using joint patent filings to obtain a partial glimpse on the nature of a firm's production network, they find no significant indirect effects while highlighting that the possible existence of indirect innovation effects is an empirical question yet to be fully investigated.

[2] It is worth noting that a nascent literature in climate finance has started to look into how supply relationships lead to an effect of downstream ESG policies on suppliers (Dai, Liang and Ng, 2021). Hege, Li and Zhang (2023) study whether climate-related innovation upstream reduces greenhouse gas emissions in downstream firms. This literature, however, does not consider the effects of carbon pricing.

[3] Dhyne et al. (2019) provide a useful overview of the basic tools in this literature.

inform policymakers accurately (Pichler et al., 2023).

We add to this literature by building on empirical work done using one of the leading production network datasets which allows us to track all business transactions across the universe of Belgian companies. By merging this data with a host of other Belgian microdata as well as data on carbon pricing regulation, emissions, and low-carbon patenting, we build on existing work in the production-network based literature by bringing the data frontier to bear on climate policy.

4 Data

Our sample draws on several confidential administrative datasets covering the universe of firms in Belgium: annual accounts filed by each firm and data covering all VAT transactions which allows us to map the entire production network of firms in Belgium. We combine these data with carbon price and treatment status data from the European Union Emissions Trading System (EU ETS), as well as with patent data from PATSTAT to capture innovation outcomes through patenting.

4.1 Production network

In order to build the domestic upstream and downstream exposure to the EU ETS, we use the dataset of Business-To-Business (B2B) transactions drawing on previous work at the National Bank of Belgium (NBB) (Dhyne, Duprez and Komatsu, 2023, Dhyne, Magerman and Rubínová, 2015). Given the mandatory reporting of VAT on sales exceeding 250 euros by all businesses in Belgium, the dataset ensures comprehensive coverage of the entire spectrum of active businesses in the country. Annual sales values within domestic supplier-buyer relationships across Belgium are derived from value-added tax (VAT) declarations, reflecting the total amount of invoices from one firm to another, excluding the corresponding VAT, in each year between 2008 and 2022.

4.2 Annual accounts

Company accounts data are obtained from the central balance sheet office at the NBB. Various firm characteristics are derived from the mandatory submissions of annual accounts by all incorporated companies with limited legal liability for tax compliance. The company accounts data provides financial and operational information for each firm, including value added, employment, and capital stocks and expenditures.

4.3 Trade

The Intrastat trade survey for transactions with the EU and the customs trade data for transactions outside the EU are also accessed through the NBB and provide details on the value and quantity of each product exported or imported by each firm to and from each destination and origin.

4.4 Prodcom

The Prodcom database, established by Eurostat, conducts a monthly survey of industrial production across all EU countries. Its primary aim is to enhance the comparability of production statistics within the EU by employing a standardised product nomenclature known as Prodcom. These codes, consisting of eight digits, with the initial four derived from NACE codes, facilitate uniformity in reporting. Prodcom encompasses the production of sectors C and D in NACE Rev. 1.1 (Mining and quarrying, and manufacturing), excluding sections 10 (Mining of coal and lignite), 11 (Extraction of crude petroleum and natural gas), and 23 (Manufacture of coke and refined petroleum products). Over the years of our sample, participation thresholds have experienced slight variations[4]. The surveyed firms represent over 90% of Belgian manufacturing production, and the raw data is aggregated from the plant-level to the firm-level.

4.5 Carbon market data

The European Union Transaction Log (EUTL) provides the main data source on the EU ETS itself. The EUTL covers EU ETS-regulated installations, from which we can derive the treatment status of firms: regulated by the EU ETS, or not. The EUTL furthermore reports verified greenhouse gas emissions at the installation-year level. We lastly add data on the carbon spot price in the EU ETS, which is publicly available from ICAP.

4.6 Innovation data

In order to measure the innovation activities of firms in our sample, we use the EPO PATSTAT database which is a vast repository of patent documentation, offering a comprehensive collection sourced from patent authorities around the globe. Within our analysis, we focus on patented inventions submitted by Belgian companies within this database. To qualify for a patent, an idea must showcase an advancement beyond the existing state of the art. Securing legal protection within a jurisdiction entails obtaining a monopoly right to commercially exploit the idea therein. In our categorisation, we employ the EPO's definitions to designate an innovation within the "clean" technological field, as in Guillard et al. (2021), relying on the International Patent Classification (IPC) codes found in PATSTAT. Specifically, we code a patent as clean if it falls within the EPO class "Y02", which capture climate change mitigation technologies.

[4]Companies participate if they have at least 20 employees or 5 million euros of annual turnover and if they produce goods that fall under the Prodcom classification. Other recent work using Prodcom data for Belgium includes Gagliardone et al. (2024).

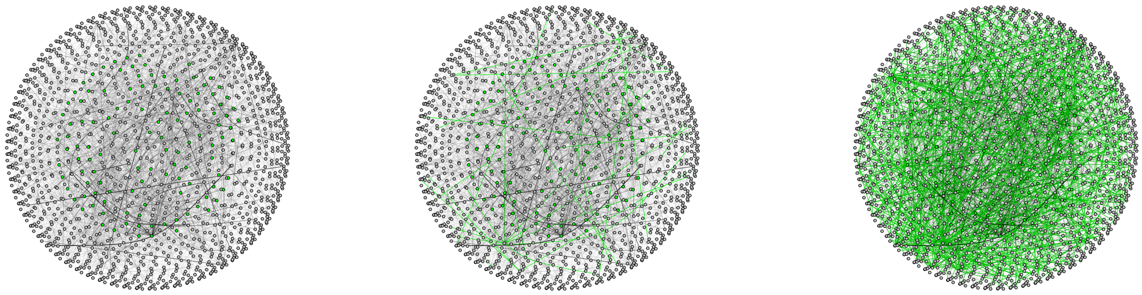
5 Descriptive statistics and stylised facts

Our sample is based on the above-mentioned sources. To align the temporal dimension, fiscal years have been annualised to calendar years, consistent with the unit of observation in the NBB B2B data. Our sample selection is refined by limiting B2B transactions to firms present in the annual accounts data, thereby excluding the self-employed. Furthermore, we focus our analysis on firms with more than one full-time equivalent employee and exclude firms that do not engage in transactions with other Belgian firms, i.e. those that exclusively sell directly to final consumers in Belgium or abroad.

Our first stylised fact is to document the importance of indirect regulation by the EU ETS in the Belgian economy. The importance of EU ETS-regulated firms for the Belgian economy is illustrated in figure 2, which shows the B2B network based on 2500 randomly selected non-ETS firms present in the data in 2012, and all EU ETS-regulated firms (the latter represented by green points). The flows of purchases between firms is depicted by the edges, of different transparency as a function of the share of those sales over the year relative to all sales. The network graph illustrates that despite the small number of firms directly subject to carbon pricing in Belgium, a large proportion of firms are indirectly supplied input from regulated firms. In addition, figure 3 illustrates those firms that are filing patents classified as clean.

Our second stylised fact is to look at at EU ETS-exposure by industrial sector. First, we count the number of firms in each sector across the economy. For each sector, figure 4 then plots the count of firms directly regulated by the EU ETS (green bars), of firms with an EU ETS-regulated supplier (orange bars) or EU ETS-regulated client (yellow bars) against the total number of firms in the sector. The figure shows that the overall number of indirect links exceeds the number of directly regulated firms, thus suggesting that the network structure of the economy is likely to be a key consideration which to take into account in analyses of the

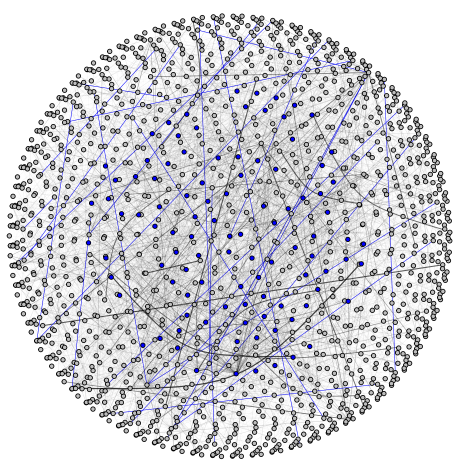
Figure 2: Business-to-Business network and ETS firms



(a) ETS - non-ETS firms **(b) First ETS edge** **(c) First and second**

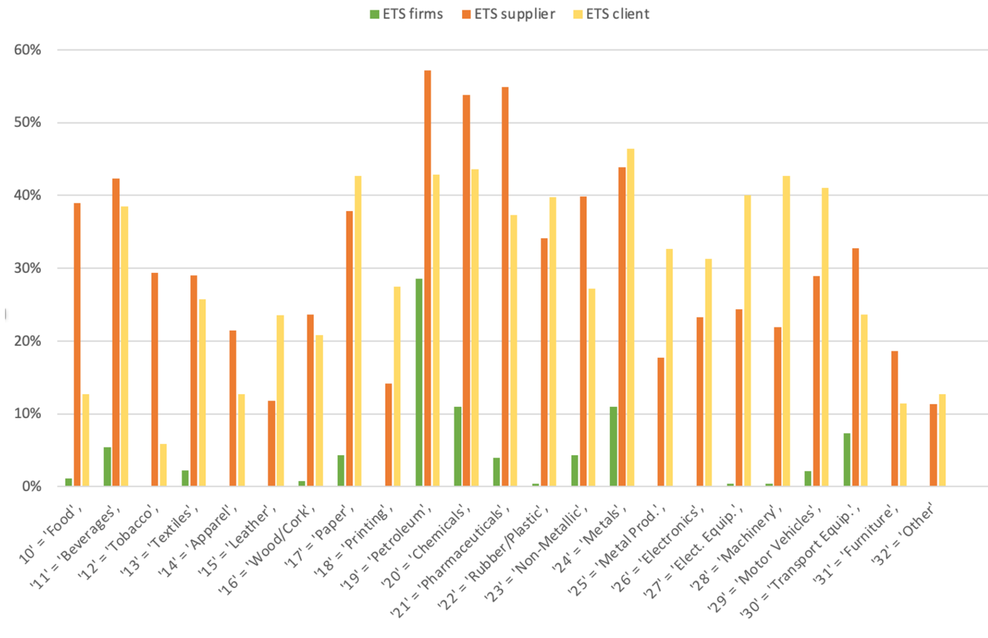
Notes. The figures show a spherical plot of network edges in 2012 between firms (a random selection of 2500 non-EU ETS firms and all EU ETS-regulated firms). The transparency of the links is proportional to the share of that link in the total purchases of a firm. Sub-figure a) represents EU ETS firms by green dots. Sub-figure b) has the sales of EU ETS firms to their direct clients in green. Sub-figure c) depicts in green these sales as well as the sales of clients of EU ETS firms.

Figure 3: Business-to-Business network and innovative firms



Notes. The figures show a spherical plot of network edges in 2012 between firms (a random selection of 2500 non-EU ETS firms and all EU ETS-regulated and firms with clean patents). The transparency of the links is proportional to the share of that link in the total purchases of a firm. The figures depicts in blue the first degree sales of clean firms (in blue), where clean is defined by patent.

Figure 4: Firms with EU ETS-regulated suppliers or clients

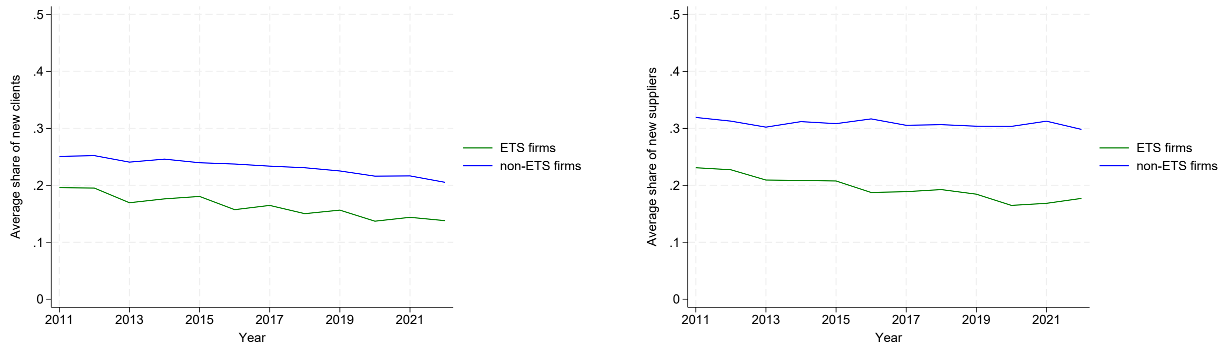


Notes. The figure shows the amount of firms out of each sectoral firm total that are directly regulated by the EU ETS (green bars), have an EU ETS-regulated supplier (orange bars) or EU ETS-regulated client (yellow bars) in their network.

economic effects of the EU ETS. Interestingly, there is substantial variation across sectors in the ratio of indirect to direct links. "29 Motor Vehicles" or "28 Machinery", for instance, contain only a limited number of companies directly regulated by the EU ETS, but indirect links are present for as many as 40% of firms in these sectors, in particular on the client side. Firms in "19 Petroleum", "20 Chemicals", or "22 Pharmaceuticals" by contrast, tend to see the largest numbers of indirect EU ETS-regulation on the supplier side.

Lastly, we look at the dynamics of a firm's production network separately by firms regulated by the EU ETS, and by firms not regulated by the EU ETS. For each year, the share of new clients or new suppliers in a firm's operations is computed, defining new clients/suppliers as those with which a firm had no sales/purchases in the four previous years. As shown in figure 5, firms directly regulated by the EU ETS have a slightly less dynamic relationships with their suppliers and clients, which could be explained by specificities of the sectors most regulated under the carbon market. It could also play a role for the diffusion of the effects

Figure 5: Dynamics of firm production network by EU ETS treatment status



Notes. The figure shows the average share of new clients (left panel) and new suppliers (right panel) out of total clients/suppliers per firm-year. Firms directly regulated by the EU ETS are depicted in green, while all other firms are depicted in blue.

of indirect carbon pricing across the wider economy.

6 Empirical Methodology and Results

6.1 Price impact

As a first step in our analysis, we examine whether the increase in the price of EU ETS allowances has prompted firms to pass these additional costs onto their clients by analyzing data from the Prodcom dataset. Although this dataset covers only a subset of firms, we are able to compute, for each firm and each year, the product-weighted firm-level change in unit prices relative to the base year. More specifically we compute:

$$\Delta\text{UnitPrice}_{i,t} = \sum_{p} \left(\ln\left(\frac{\text{sales}_{i,t,p}}{\text{quantity}_{i,t,p}}\right) - \ln\left(\frac{\text{sales}_{i,2012,p}}{\text{quantity}_{i,2012,p}}\right)\right) \times \frac{\text{sales}_{i,2012,p}}{\text{TotalSales}_{i,2012}}$$

for each year t and firm i such that for each product p we weigh by its share in the firm's sales in 2012 the change in its unit price between 2012 and year t. To consider the impact of ETS participation on the unit price, we estimate the following regression for years after

Table 1: ETS Impact on Unit Prices (2016-2020)

Dependent variable:	Δ Unit Price (1)	(2)
ETS firm	0.147	0.142
	(0.183)	(0.150)
Sector fixed-effect	No	Yes
Number of observations	7,945	7,482
Number of firms	1,850	1,780

Notes: OLS regressions. The dependent variable measures the product-weighted difference between in the log of unit prices at the firm-level in each year relative to 2012. The regulatory status (ETS firm) is a dummy. Robust standard-errors (clustered at the firm level) in parentheses.

2015:

$$\Delta\text{UnitPrice}_{i,t} = \beta_1 \text{ETS}_i + \alpha_t + \alpha_n + \epsilon_{i,t}$$

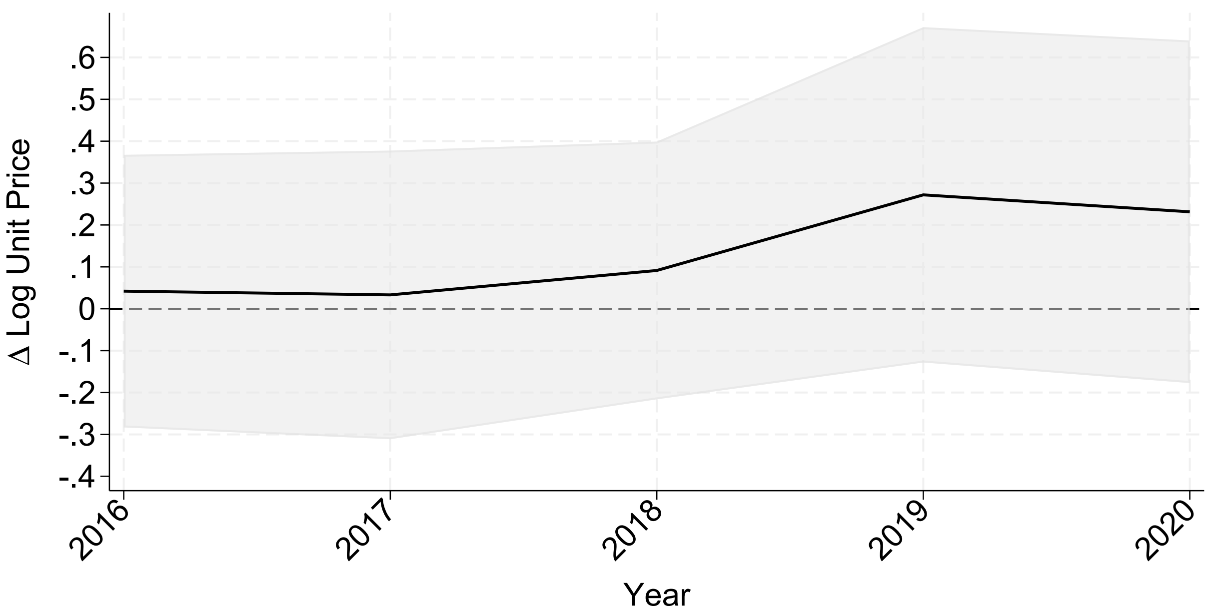
where ETS is a dummy as to whether the firm is part of the EU ETS, and α_n, α_t are sector and year fixed-effects.

The results presented in Table show that there was no significant increase in prices charged by ETS firms relative to non-ETS firms after 2015, years during which the ETS price increased strongly. We also find, when interacting the ETS dummy with each year that there is a slightly stronger effect in more recent years, though statistically insignificant, and future versions of this paper will intend to incorporate more recent waves of the Prodcom dataset to explore this further.

6.2 Indirect impacts on economic outcomes

We adopt a shift-share design that leverages the pre-sample links in the production network and and a plausibly exogeneous increase in the EU ETS carbon price. Specifically, we fix the exposure to EU ETS firms in 2012, the last year prior to our sample period. This follows standard practice from the network literature to identify shocks to production networks. During our sample period from 2013 onwards, the EU ETS price more than doubled. This

Figure 6: Yearly estimates of EU ETS treatment effect on Unit Prices



Notes. The figures plot year-specific treatment effects of the ETS on firm level unit prices relative to unregulated firms and against a 2012 baseline. The coefficient estimates are obtained from the interaction of the ETS regulation dummy, and year indicators in an OLS regression where the dependent variable is $\Delta UnitPrice$. Shaded areas represent 95% confidence intervals. Robust standard errors are clustered at the firm level.

gives us the shift in the shift-share design. Exogeneity could, however, still be violated in the presence of long-run sectoral or regional trends that operate via firm characteristics that correlate to EU ETS exposure.

We distinguish a number a potential pathways to impact. Firstly, we consider the direct impact of a change in ETS carbon prices on firm i, $\Delta p_i^D = ETS_i \Delta p_{CO2}$, where ETS_i is a dummy equal to 1 for firms regulated by the EUETS and lower case letters indicate logs; e.g. $p_{CO2} = \ln P_{CO2}$. Hence the price change is 0 for firms not covered by the ETS.

We consider two types of indirect effect transmitted via the production network.[5] Firstly, upstream effects, and secondly general downstream effects. We discuss these in turn. We would expect upstream effects to primarily be transmitted via cost past through; i.e. upstream firms pass on on (some) of the cost increase induced via the ETS via higher prices. Downstream subsequently respond to this by reducing their output (due to higher cost) or substituting away from the affected inputs. Although we have not observed this to be the case in section 6.1, other transmission channels are possible. For example, supplier relationships could help overcome knowledge barriers about new technologies, or the quality or type of inputs supplied could also be affected. For each firm i we compute the share of purchases in the base year from ETS firms in total purchases.

We follow a similar approach for downstream linkages and compute in the base year the share of total sales made to firms that are part of the EU ETS. The expected sign of downstream effects would be ambiguous a priori and likely depends on the type of good sold by firm i. If i sells close carbon free substitutes to inputs associated with carbon emissions - e.g. equipment helping to reducing emissions - we might expect a positive effect on sales of i. Alternatively, we would expect that increased costs and potentially reduced production downstream have negative effects on i as well.

To examine the direct and indirect impact of carbon pricing on firm outcomes, we conse-

[5] There are potentially more, which we will explore in future work.

quently implement regressions of the form

$$\Delta Y_{it} = \beta_u ShareETS^{up} + \beta_{ETS} ETS + \beta_d ShareETS^{Down} + \Delta\epsilon_{it}$$

where Y_{it} represents a number of different outcome variables such as (log) value added, employment, investment.

We base our measures of EU ETS exposure $ShareETS^{Up}$ abd $ShareETS^{Down}$ on production linkages in 2012, which predates our sample (2013 onwards) and the recent increase in carbon prices. A fixed production network approach is the standard taken in the literature, such as in recent contributions on firm heterogeneity (Bernard et al., 2022) or domestic micro-level reactions to foreign demand shocks (Dhyne et al., 2022)

Applying the methodology described above as a first step in our analysis, we focus here on the impact exposure to the EU's carbon price on the growth of total sales between 2013 and 2016 to 2022. Table 2 reports the results. Neither Direct, Upstream or Downstream exposure to the policy significantly impact the value-added, employment, investmnet, exports or imports of a firm. Further heterogeneity analysis will focus on understanding how different sectors or time periods might see different patterns in these findings.

Table 2: The Effect on value-added, employment and trade - 2016-2022

	(1) Δln(Value-Added)	(2) Δln(Employment)	(3) Δln(Investment)	(4) Δln(Exports)	(5) Δln(Imports)
ETS (Direct)	0.028 (0.021)	0.002 (0.017)	0.114 (0.083)	-0.177 (0.121)	-0.026 (0.118)
Upstream (Share of Purchases from ETS firms)	-0.026 (0.018)	-0.003 (0.017)	0.132 (0.102)	-0.203 (0.211)	-0.272 (0.203)
Downstream (Share of Sales to ETS firms)	0.006 (0.011)	-0.013 (0.011)	-0.071 (0.057)	0.068 (0.127)	-0.157 (0.108)
Year Controls	Yes	Yes	Yes	Yes	Yes
Sector Controls	Yes	Yes	Yes	Yes	Yes
Observations	376,547	376,547	284,453	44,126	66,583
Firms	72,634	72,634	59,958	9,033	14,077

Table 3: The Effect on client and supplier portfolios - 2016-2022

	(1) Δ Share of New Suppliers	(2) Δ Share of New Clients
ETS (Direct)	-0.007	0.009
	(0.005)	(0.010)
Upstream (Share of Purchases from ETS firms)	0.018***	0.028***
	(0.006)	(0.009)
Downstream (Share of Sales to ETS firms)	0.009**	-0.008
	(0.004)	(0.007)
Year and Sector Controls	Yes	Yes
Observations	376,547	376,547
Firms	72,634	72,634

Notes: OLS regressions. The dependent variables are the yearly changes between 2013 and each year in the share of suppliers or clients of the firm that are new, defined as not having been trading with that firm in the past 4 years. Each regression includes year and 1-digit sector controls. The Upstream and Downstream explanatory variables are the share of Purchases and Sales from/to ETS firms in the base year. The sample includes the years between 2016 and 2020. Robust standard errors in parenthesis. Significance levels are indicated as * 0.10, ** 0.05, *** 0.01.

6.3 Dynamics of the supply chain

To examine how firms adjust their production networks in response to rising carbon prices, we calculate, for each firm and year, the proportion of clients that were new, i.e., those not present in the firm's sales transactions over the preceding four years. A similar metric is constructed for suppliers. Table 3 presents the results of a regression analysis using these metrics as dependent variables, with controls for the years 2016 to 2022.

We find that firms who source a large share of their supplies from ETS firms are more likely to increase their annual share of new suppliers. One hypothesis could be that in the face of potential increases in prices, firms diversify their portfolio of suppliers. It is also the case that firms with a larger share of their sales to ETS firms also increase their share of new suppliers. This could signal a change in the type of products sold to these firms, requiring a change in the composition of products and inputs, and hence suppliers.

Table 4: The Effect on Patents - 2016-2020

	(1) Δ Total Patents	(2) Δ Total Patents	(3) Δ Clean Patents	(4) Δ Clean Patents
ETS (Direct)	0.146***	0.144***	0.082***	0.081***
	(0.042)	(0.042)	(0.023)	(0.023)
Upstream (Share of Purchases from ETS firms)		0.013		0.002
		(0.010)		(0.003)
Downstream (Share of Sales to ETS firms)		0.009		0.007**
		(0.008)		(0.003)
Year and 2-digit Sector Controls	Yes	Yes	Yes	Yes
Observations	203,789	203,789	203,789	203,789
Firms	50,823	50,823	50,823	50,823

Notes: OLS regressions. The dependent variables are the change between 2013 and each year of the logarithm of one plus the stock of total patents (columns 1 and 2), and and the stock of clean patents (columns 3 and 4). The Upstream and Downstream explanatory variables are the share of Purchases and Sales from/to ETS firms in the base year. Each regression includes year and 2-digit sector controls. The sample includes the years between 2016 and 2020. Robust standard errors in parenthesis. Significance levels are indicated as * 0.10, ** 0.05, *** 0.01.

6.4 Innovation

In light of the results above, we are keen to understand how adjustments to rising ETS prices in the composition of suppliers and customers might also be reflected in an increase of innovation. Or whether higher ETS prices incentivise ETS firms themselves to innovate more, in particular in clean technolobies. Applying the same approach as above, we take as outcome variables the change in patenting from 2013 in Table 4. The dependent variables are constructed as the change in the logarithm of one plus the total stock of patents - total number of patents in the first two columns, and clean patents in columns (3) and (4). In line with the existing literature, we find a significant effect on patenting of firms being regulated in the EU ETS. In column (4), we also find that having a large share of clients regulated by the EU ETS is associated with an increase in clean patenting. This could signal the demand by regulated firms for clean inputs or technologies. Future versions of this paper will include more recent data on patents and explore further this finding.

7 Conclusion

This paper provides insights into the far-reaching effects of carbon pricing within the European Union Emissions Trading System (EU ETS). By leveraging a unique dataset that maps the production networks of Belgian firms, we demonstrate that carbon pricing has effects not only on regulated firms but also on unregulated firms connected to them via supplier and customer relationships. Our findings reveal that indirect carbon pricing—through these production linkages—plays a significant role in shaping economic outcomes such as clients and suppliers portfolios and innovation, with potentially important implications for policymakers aiming to fine-tune market mechanisms for decarbonisation.

We highlight several key takeaways. First, most firms are indirectly connected to EU ETS-regulated entities, either upstream or downstream, and this varies across sectors, suggesting that the reach of carbon pricing extends well beyond the directly regulated firms. This underscores the importance of considering the entire production network when designing and evaluating carbon markets. Second, our results show that while direct EU ETS participation did not significantly lead to price increases, the trend of more recent years highlights the need for further analysis into how firms manage cost pass-through in carbon-intensive supply chains. Third, we find that on average the increase in the ETS allowance price was not associated with a decrease in employment or value-added, although future versions of this paper aim to explore any heterogeneous effect that this average might be concealing. Finally, our investigation into innovation outcomes reveals that carbon pricing spurs clean technology development and overall patenting, both for directly and indirectly regulated firms, aligning with the EU's broader decarbonisation goals.

The findings contribute to the growing literature in climate economics by extending the understanding of carbon pricing's indirect effects, thus addressing a significant gap. Traditional analyses have largely focused on directly regulated firms, yet our research emphasises that the impacts permeate throughout the broader economy. This insight has clear implications for the design of carbon markets, particularly as the EU prepares for more comprehensive coverage in future phases of the ETS, including sectors such as road transport and buildings.

Moving forward, future research should continue to explore the heterogeneous effects of carbon pricing across different industries and types of firms, particularly in understanding how certain firms manage to mitigate the potential negative impacts through innovation and strategic adaptation. Additionally, examining the role of market structure and firm-level characteristics in moderating these effects will be crucial for policymakers seeking to optimise the balance between economic growth and environmental sustainability.

In conclusion, our research presents evidence that the effects of carbon pricing reverberate throughout the production network, suggesting that carbon market designs that account for these indirect effects may hold the key to achieving low-carbon transitions at the least economic cost. Understanding the full spectrum of carbon pricing impacts, both direct and indirect, will be essential as economies globally strive to meet ambitious climate targets in the coming decades.

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