Financial frictions, technological adoption, and corporate emissions*

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Abstract

This paper analyzes how financial frictions and policies to alleviate them shape total emissions and the effectiveness of carbon pricing. We present empirical evidence that less financially constrained firms operate with lower emission intensities and are better able to improve their environmental performance in response to higher carbon prices, in part by drawing on external finance. We propose a heterogeneous-firm general equilibrium model featuring endogenous adoption of better capital vintages subject to financial frictions that quantitatively matches our empirical evidence. Simulations of the calibrated model show that relaxing financial constraints—including green-biased lending—raise total emissions, despite fostering adoption of cleaner technologies, because they increase GDP. Moreover, financial frictions give rise to additional channels and larger economic costs of higher carbon prices.

JEL Codes: Q55, H23, O44, G30.
Keywords: Climate Change, Emissions, Financial Constraints, Financial Frictions, Productivity, Technology Adoption, Capital Vintages.

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1 Introduction

Despite reduced consensus since the Paris agreement came into effect in 2016, mitigating climate change remains a priority for many governments around the world. Many jurisdictions have introduced green financial sector policies, partly motivated by political challenges to introducing or raising carbon taxes (Blanchard et al., 2023). For example, Europe aims to complement carbon pricing with large scale green lending supported by the European Investment Bank (EIB) in addition to shifts in bank supervision and regulation and collateral policy being considered by the ECB.[1] This raises an important question on which the literature offers little evidence: how do financial frictions and policies to alleviate them shape total emissions and the effectiveness of carbon pricing?

In this paper, we provide new empirical and theoretical evidence on this question. We begin by presenting sharp empirical evidence that less financially constrained firms operate with lower emission intensities and are better able to respond to carbon pricing. When faced with higher carbon prices, less constrained firms appear to use their ability to draw on external finance to make meaningful improvements to environmental efficiency relative to more constrained firms. We propose a heterogeneous-firm general equilibrium model featuring endogenous adoption of technology embedded in newer vintages of capital subject to financial frictions that quantitatively matches our empirical evidence. Counterfactual simulations from our calibrated model show that, in general equilibrium, attempts to relax financial constraints—including green-biased lending—raise total emissions because they increase GDP. While stronger green bias can help cut emissions, holding carbon taxes fixed, this comes at significant cost to GDP. Our model also reveals additional channels of the economic costs of higher carbon prices.

We use verified data on emissions for European manufacturing firms in energy-intensive industries subject to carbon pricing. Emissions data from 2005-2021 for 3,200 manufacturing firms are from the European Union (EU) Emission Trading Scheme (ETS).[2] We merge the emissions data with balance sheet and income statement data

[1] The EIB's website points to financing for €550 billion in new investments to support the green transition since 2021. The ECB's website details initiatives under consideration for supervision, regulation, and collateral policy. Central banks in China and Japan have also introduced special lending facilities for banks to facilitate loans for green investments.

[2] The EU ETS covers manufacturing firms engaged in energy-intensive activities. Emissions data includes both carbon dioxide and other greenhouse gases, reported in equivalent terms, when directly generated at the covered plant (Scope 1).

from Orbis (Letout, 2021). Crucially, this approach allows us to use verified data on emissions for both small firms—which are more likely to face binding financial frictions (Beck et al., 2005)—and large firms. In 2021, firms in our sample emitted 315 Megatons of greenhouse gas equivalents or approximately 40% of European manufacturing emissions.

Financial constraints do appear to shape environmental performance at the firm level. We construct net worth—capturing unused borrowing capacity—as in Ottonello and Winberry (2024). Importantly, we make granular comparisons by restricting attention to variation within firms in the same 4 digit SIC industry and country.[3] Firms with higher net worth have smaller environmental footprints relative to the scale of their operations: they have lower emissions relative to value added than within-industry peers.

Financial constraints also affect the ability of firms to adjust to exogenous changes in carbon prices. Specifically, we explore how firms with high net worth respond to exogenous carbon price shocks relative to peers, again within narrowly defined industries. We use a series of exogenous shocks to ETS carbon prices constructed by Känzig (2023) following the high frequency monetary policy literature (Kuttner, 2001; Gurkaynak et al., 2005; Gertler and Karadi, 2015; Nakamura and Steinsson, 2018).

The ability to draw on external finance appears to allow less constrained firms to differentially cut emissions in response to higher carbon prices with little relative impact on the scale of production. In response to an 1% exogenous increase in carbon prices in year t, the subsequent year less constrained firms increase borrowing by about 0.24% more than firms that face more binding financial constraints. Likely aided by their higher access to external finance, less constrained firms cut emissions by an additional 0.11%, with no differential impact on the scale of their production as measured by value added. Emission intensities—emissions scaled by value added—therefore also relatively fall by 0.16%, suggesting that these firms make investments that improve environmental efficiency.

Intriguingly, better access to external finance seems to allow for such improvements in response to higher carbon prices only within firms far from the productivity frontier in their industry. We construct productivity at the firm-year level following Asker et al. (2014). Better access to external finance plays little role in shaping firms' ability to

[3] An example highlighting the granularity of the industry classification we use is that forging of raw steel is a distinct industry from transformation of steel into specific products.

adapt to higher carbon prices within firms with high productivity within their country and industry. Indeed, our results are concentrated within firms with low productivity. Among low productivity firms, less constrained ones increase borrowing by 0.71% more than firms facing binding financial constraints one year after a 1% exogenous rise in the carbon price. And they are able to cut emissions by 0.10% more relative to more constrained firms.[4]

To rationalize these findings, we propose a tractable continuous time heterogeneous-firm general equilibrium model of investment across different capital vintages subject to financial constraints. Firms vary on two dimensions in the model: in their productivity, and net worth. Importantly, firms face leverage limits that depend on their net worth as in Ottonello and Winberry (2024). The model includes endogenous entry and exit. Key features of the production function include decreasing returns to scale—pinning down optimal scale for each firm—and complementarity between energy and capital. Firms make endogenous dynamic decisions about investments in different vintages of physical capital. A key ingredient of the model is that more efficient vintages embed technologies that enhance productivity, cut energy consumption, and reduce emissions (Capelle et al., 2024).

The key tradeoff that firms face in the model is between investing in more efficient capital vintages and scaling up their capital stock. On one hand, firms prefer better vintages because they are more productive and help cut energy consumption and emissions. On the other hand, better vintages are also more expensive. This generates a pecking order of vintages. The most constrained firms—young firms with very low net worth—are far smaller than their optimal scale as the leverage constraint binds tightly. These firms choose to use, less efficient vintages as these allow them to operate at a larger scale. As firms grow and accumulate net worth, they progressively upgrade to better, more productive vintages. Fully unconstrained firms can operate at their optimal scale with the best vintage.

We carefully calibrate the model to allow for quantitative counterfactual analysis. We match important moments of the empirical distributions of firm size and productivity, as well as evidence from the literature on the extent to which capital embedded technologies help cut emissions holding energy consumption fixed (Capelle et al., 2024). We target data on energy consumption and average leverage for European manufacturing

[4] Our results are robust to measuring financial constraints through leverage rather than net worth and to utilizing the age of the capital stock used in production to proxy for firm productivity.

firms. Finally, we match both past and expected future levels of carbon prices.

Our model both qualitatively and quantitatively matches our empirical evidence: less constrained firms are able to generate bigger improvements in environmental performance when carbon prices rise. High net worth firms are more likely to be able to respond to higher carbon prices by quickly upgrading to a more productive and emission and energy efficient vintage. In contrast, the most constrained firms accumulate net worth slowly, and therefore need more time to jump up the vintage ladder. Regression results utilizing simulated data from the model, quantitatively match our empirical findings: less constrained firms cut emission intensities by .05 log points in response to a 1 log point increase in carbon prices. This tight link with the data on an untargeted moment offers strong validation for the model.

Counterfactual simulations from the calibrated model yield three key insights. First, holding carbon taxes fixed, relaxing financial constraints raises—rather than lowers—emissions in general equilibrium. Conceptually, the impact on emissions of relaxing financial constraints is not clear. On one hand, looser financial constraints allow some firms to upgrade to newer, more efficient vintages and reduce emissions relative to firm size. On the other hand, looser constraints allow firms to increase their capital intensity, which increases energy consumption due to the complementarity between capital and energy. This increases emissions relative to firm size. Moreover, firms—and the economy—grow, raising emissions holding emission intensities fixed. Quantitatively, this final channel dominates: GDP grows significantly when financial frictions are eased, with small effects on emissions from the earlier channels. Eliminating financial frictions in our calibrated model results in a 31% increase in total emissions, largely due to a 27% increase in GDP.

Second, green financial policies can help further improve environmental efficiency, but not sufficiently strongly to offset economic growth and cut total emissions. Concretely, we consider policies—such as public lending or guarantees as currently deployed in Europe—that relax borrowing constraints specifically for upgrades to green investments. We use counterfactual simulations to consider two types of shifts towards greener financial policies. First, we consider expanding the scale of these policies holding the set of green vintages covered fixed. As with a broad elimination of financial constraints, this incentivizes the adoption of newer, greener capital vintages, but also increases overall emissions as the economy also grows. A relaxation of the maximum leverage ratio from 2.2 to 2.4 of net worth raises emissions by 1.8% and increases GDP

by 3.7%. Second, we eliminate financial support for all but the greenest capital vintages. Doing so could help cut emissions, even holding carbon taxes fixed, but at a significant GDP cost. Shifting from financial sector policies with no green bias to policies exclusively targeting the greenest vintage cuts emissions by 3.2% in our model, but also cuts GDP by 3.5%. The introduction of green financial policies, holding the policy mix fixed, therefore does not offer an easy way to reduce emissions.

Finally, our modeling approach reveals new channels of the economic costs of higher carbon prices. When carbon taxes rise, GDP is immediately adversely affected as higher energy costs force firms to shrink. The presence of financial frictions leads to two additional channels that amplify this short-term effect and take time to materialize. The first is that young, constrained firms cannot grow as fast, as higher costs of emissions slow accumulation of net worth. The second is that entry rates fall because of smaller expected profits. In combination, these channels shift the distributions of net worth and firm size to the left, lowering total output. We consider a permanent increase in the carbon tax from €30 (pre-pandemic levels) to €100 per ton of carbon dioxide equivalent. This cuts emissions by 68.5% and lowers steady state GDP by 13%. These costs take time to materialize—as higher counterfactual net worth would only accumulate slowly over time. These new channels, which are quantitatively important, are not present in prior work examining carbon taxes in models that include real investment frictions but not financial frictions (Capelle et al., 2024; Finkelstein Shapiro and Metcalf, 2023).

Literature and contributions. This paper presents evidence on how financial frictions—and policies that aim to improve access for financially constrained firms—matter for aggregate emissions and the effectiveness of carbon pricing. Our empirical and theoretical results make three main contributions to the literature.

First, we present new empirical evidence using micro data that less financially constrained firms are better able to adapt to carbon pricing. Specifically, using verified data on emissions for a large group of firms including small, unlisted firms, we consider how emissions respond to exogenous carbon price shocks (Känzig, 2023). We also consider the evolution of debt and present evidence that less constrained firms far from the productivity frontier are better able to adjust, speaking to mechanisms. Important prior work offers evidence on the role of financial frictions (Accetturo et al., 2022; Fang et al., 2023; De Haas et al., 2024; Martinsson et al., 2024) and on the impact of carbon

pricing (Martin et al., 2014b,a; Colmer et al., 2024) individually.[5] There is little prior empirical evidence considering both financial frictions and carbon prices. Berthold et al. (2023) examine how stock prices differentially react to exogenous carbon price shocks for dirtier European firms based on self-reported and potentially imputed data on emissions, also drawing on work by Känzig (2023). Their focus on stock prices means that they cannot consider small, unlisted firms. Carradori et al. (2023) show that more levered firms covered by the EU ETS are able to deliver small cuts in emissions. However, they do not consider exogenous variation in carbon prices. Kaldorf and Shi (2024) show that less financially constrained firms cut emissions by less in response to carbon taxes across a panel of 33 countries. They also use self-reported and potentially imputed emissions data and do not consider exogenous carbon price shocks. Xu and Kim (2022) consider how financially constrained firms respond to more stringent environmental regulations across a broad range of pollutants and do not focus on greenhouse gas emissions.

Second, we consider how financial frictions shape endogenous technological adoption in a general equilibrium macro model of firm dynamics. Our model combines a Hopenhayn (1992) framework, in which firms face decreasing returns to scale and exogenous idiosyncratic productivity shocks, with financial frictions as in Khan and Thomas (2013) and Ottonello and Winberry (2024). Financial frictions impede firms from reaching their optimal size. The key theoretical novelty here is to embed into this framework a technological choice of vintages as in Capelle et al. (2024). The interaction of financial frictions with endogenous vintage choice gives rise to a trade-off between upgrading to newer vintages and scaling up the capital stock, similar to complementary work by Lanteri and Rampini (2025). The pecking order of vintages—a key and novel result of this paper—is the outcome of this trade-off. Importantly, we incorporate a production function for emissions that accounts for newer capital vintages in a way that is consistent with empirical evidence presented by Capelle et al. (2024).

Third, we contribute to a growing theoretical literature on how the macroeconomic impact of environmental policies depends on firm-level heterogeneity by incorporating financial frictions that slow technological adoption.[6] Prior work has considered carbon

[5] Colmer et al. (2024) show that, on average, firms appear to be able to adjust to higher carbon prices seemingly at little cost. They also emphasize room for gains for firms far from the productivity frontier, but do not focus on the role of financial frictions.

[6] See Bilal and Stock (2025) for a comprehensive recent review of the wider literature on macroeconomic aspects of climate change.

pricing and investment subsidies when firms differ in their use of technologies and are subject to real investment frictions but not financial frictions (Capelle et al., 2024; Finkelstein Shapiro and Metcalf, 2023; Kim, 2023; Klenow et al., 2024). In this paper, we highlight new channels stemming from financial frictions. We find that the impact of financial frictions on total emissions is theoretically ambiguous, as looser financial frictions can allow firms to make upgrades that improve efficiency but also allow the economy to grow. Quantitatively, we find that growth in GDP dominates and that policies aiming to relax financial constraints raise total emissions—even when such policies are green biased. Moreover, we find that financial frictions exacerbate rather than attenuate the costs of carbon pricing.[7]

The remainder of this paper is structured as follows. Section 2 provides institutional background on the EU ETS. Section 3 describes the data. Section 4 discusses our empirical results. Sections 5, 6, and 7 respectively discuss the model set up, properties, and calibration. Section 8 discusses results from counterfactual simulations of our calibrated model. Section 9 concludes.

2 Institutional background on the EU ETS

The EU Emissions Trading System (EU ETS) is a key component of the European Union's strategy to reduce greenhouse gas (GHG) emissions. It employs a cap-and-trade approach (Schmalensee and Stavins, 2017), setting a limit on the total amount of GHG emissions that can be emitted by all participating installations, and allowing firms to trade allowances for such emissions. Each allowance permits the holder to emit one tonne of CO2 equivalent. Companies must acquire these allowances either through auctions, free allocations, or by purchasing them to other firms.

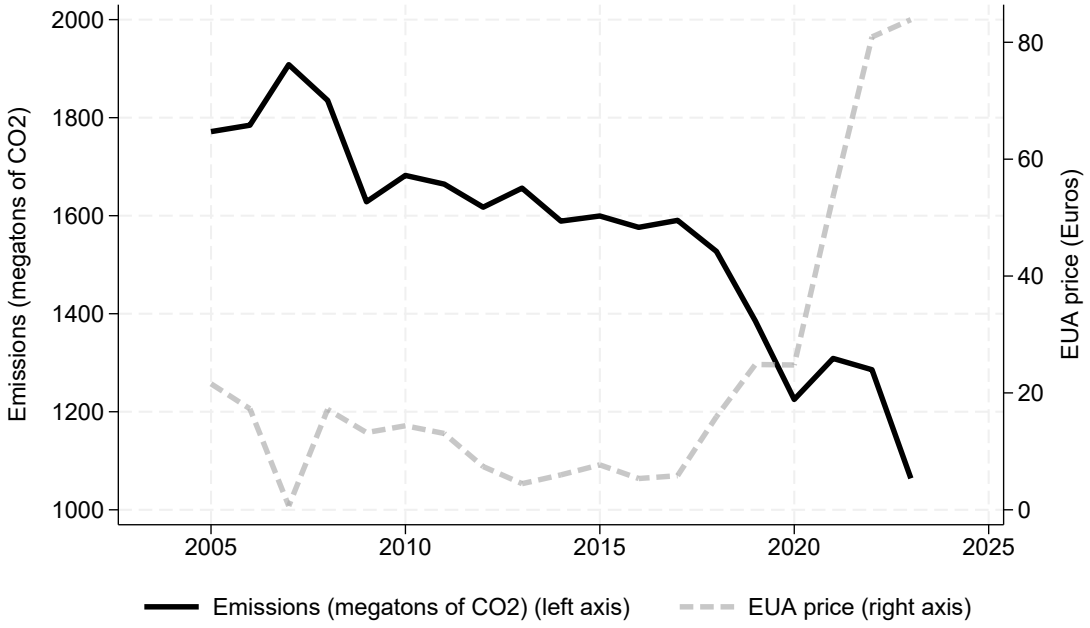
The trading of allowances creates a market price for carbon emissions. The emissions cap is gradually reduced each year to bring total emissions down over time. As the cap decreases, the supply of allowances diminishes, leading to higher carbon prices that incentivize reductions in emissions.

An ETS, a price-based tool similar to carbon taxes, is more efficient than imposing specific emissions reductions targets to individual firms or mandating the use of certain

[7] Our paper offers a dynamic quantitative model that incorporates how financial frictions shape the impact of carbon pricing. See Heider and Inderst (2022); Haas and Kempa (2023); Döttling and Rola-Janicka (2024); Herweg (2025) for related theoretical work.

green technologies or production processes (Ellerman et al., 2003). The EU ETS has been operational since 2005. Figure 1 shows the evolution of the aggregate emissions covered by the EU-ETS and of the carbon allowance price determined by the system.

Figure 1: Evolution of EUA spot prices and overall emissions under the ETS



Notes: This figure shows the evolution of the aggregate emissions covered by the EU-ETS and of the carbon price determined by the system. EUA prices denote year-end spot prices for carbon allowances under the ETS.

Emissions are measured at the installation level.[8] The inclusion of installations in the EU ETS is primarily determined by sector-specific capacity thresholds. For instance, installations which manufacture glass, including glass fiber, are covered by the EU ETS if they possess a production capacity above 20 tonnes per day. Firms may own multiple installations, and it is possible that only a subset of these are covered by the EU ETS.

3 Data sources

We combine firm-level data on emissions, balance sheets, and income statements for more than 3200 manufacturing firms, headquartered in 30 European countries covered

[8] Installations are stationary technical units where activities covered by the EU ETS are carried out.

under the EU Emissions Trading Scheme between 2005 and 2021.[9]

Emissions data. Data on verified annual emissions and emissions allowances at the installation level are from the European Union Transactions Log (EUTL hereafter), which is the central reporting and monitoring tool of the EU ETS. We aggregate the data to the firm level to match the aggregation of other data sources. We calculate it by summing the emissions from all installations associated with each firm.

The EUTL only records and reports CO2 equivalent Scope 1 (direct) emissions. The EU ETS currently covers approximately 40% of overall emissions across the EU, primarily focusing on power generation and manufacturing sectors.

Emissions for each installation are verified under an 'ETS Compliance Cycle'. This annual compliance procedure for monitoring, reporting and verification applies to all operators—the entities operating each account and installation—covered under the ETS. Data for each year must be verified by an accredited verifier within March of the following year.[10] Subsequently, the operators must surrender an equivalent number of allowances for that year. If they fail to do so, operators face a €100 penalty for each tonne of excess emissions.[11] We can therefore draw on reliable firm-level data on emissions.

Balance sheet and income data. We gather annual firm-level balance sheet and income statement data from ORBIS, a comprehensive global database covering both public and private firms. The presence of private firms is particularly important for our analysis, as these firms are generally smaller than publicly listed ones and more likely to be financially constrained (Beck et al., 2005).

Key variables present in the data include value added, total assets, tangible fixed assets, current assets, short-term and long-term debt, number of employees, and material costs.

Merging and cleaning. We merge firm-level EU ETS and ORBIS data utilizing a publicly available crosswalk from the EU Joint Research Center (Letout, 2021).[12] We keep

[9] The 30 countries include the EU member states plus Iceland, Liechtenstein and Norway (members of the EU FTA).

[10] The European Commission provides templates to be used for annual emission, verification, and other reports.

[11] Payment of the penalty does not negate the surrender obligation.

[12] The crosswalk attributes each combination of EU ETS and ORBIS firms a similarity score on their standardized names, postcodes, and cities using a fuzzy match algorithm. From this crosswalk we filter

observations where there is available information on both emissions and financials, and focus on firms in the manufacturing sector.

Our final dataset covers 85% of overall ETS manufacturing emissions on average. Annex Figure A1 shows the annual emissions coverage of our cleaned sample relative to the overall EU-ETS manufacturing emissions between 2005 and 2021.

Construction of variables. We construct several additional variables of interest. We measure a firm's environmental performance through its emission intensity, which we define as the ratio of its emissions and value added.

We measure the extent to which a firm is financially unconstrained through its net worth, defined as the sum of tangible fixed and current assets minus total debt.[13] Net worth captures the difference between assets which can be used as collateral and the existing debt stock—unused borrowing capacity. Ottonello and Winberry (2024) argue that firms with low net worth face more binding financial constraints. These firms prioritize physical capital rather than R&D investments, suggesting that they have not reached their optimal size. In contrast, as firms accumulate net worth, they shift toward innovation-intensive activities.

As we do not have information on product-level prices, we estimate TFP from revenue data as in Asker et al. (2014).[14] Following Capelle et al. (2024), we estimate a firm's age of capital by drawing on the perpetual inventory method for calculating the size of capital stocks.[15]

Carbon prices and shocks. We obtain daily carbon spot prices for EU ETS allowances from Bloomberg. To match the annual frequency of the emissions and firm financials data, we calculate annual averages of the daily carbon prices.

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out to include firms which satisfy one of the following criteria: (1) The similarity score for names is greater than 90%, (2) the similarity score for names is greater than 60% and the similarity score for post-codes is 100%, (3) the similarity score for names is greater than 60% and the city in the ORBIS Database is the same as the city in the EUTL database, or (4) the similarity score for names is greater than 60% and the first word in the ORBIS and ETS cities are the same.

[13] Tangible fixed assets are defined as all tangible assets on the books of the firm such as buildings and machinery. Current assets are the sum of short term receivables from debtors and customers, trade inventories and other current assets, defined as short term receivables from all other sources, short term investments and cash balance.

[14] This approach uses input expenditure shares to inform estimates of production functions.

[15] We weigh all past investments (after accounting for depreciation) by the number of years since the investment took place, and divide by the sum of undepreciated investments.

Our data on carbon price shocks comes from Känzig (2023), who computes daily carbon policy surprises as the percentage change in the European Union carbon allowance (EUA) futures price on days when regulation shifts expectations of the supply of emission allowances. This approach isolates exogenous variation in carbon prices.[16]

4 Results

4.1 Stylized facts

How do financial constraints shape firms' environmental performance? Financially constrained firms may lack the capacity to raise funds to undertake the necessary investments to become greener. A reduced ability to finance investments may result in both a larger environmental footprint and lower productivity.

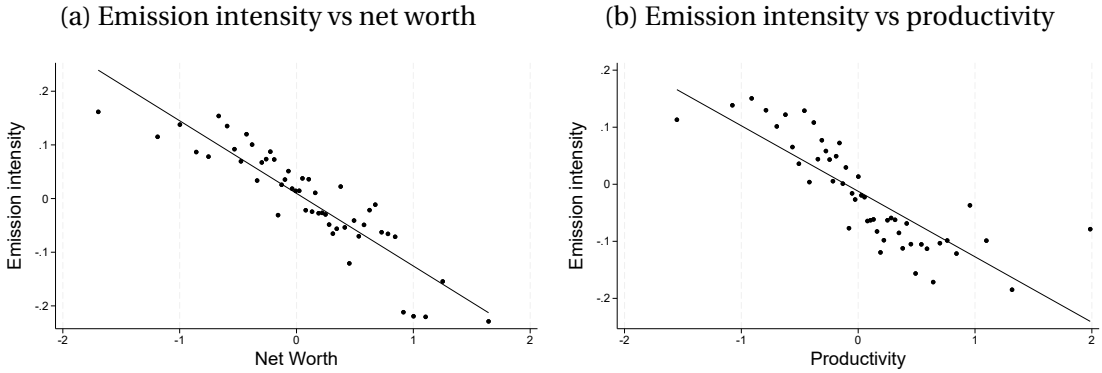
Indeed, firms with lower levels of net worth, which face tighter financial constraints, exhibit higher emission intensities (Figure 2 panel a). Moreover, firms with higher emission intensities tend to be less productive (panel b), suggesting that they have the potential to enhance their environmental performance by moving closer to the productivity frontier.[17]

Does the poorer environmental performance of firms facing financial constraints mean that they are less responsive to climate policies? Is access to financing particularly relevant for firms that are far from the productivity frontier with large potential gains from upgrading their technology?

[16] Känzig (2023) aggregates the daily surprises into a monthly series, which we further aggregate into an annual frequency.

[17] Figure 2 plots variables residualized against industry × country × year fixed effects. Figure A2 shows that results are robust to residualizing against firm + year fixed effects.

Figure 2: Less financially constrained and more productive firms have lower emission intensities



Notes: The figure displays binned scatter plots of emission intensities (the logarithm of emissions over value added) against the net worth (panel a) and the productivity (panel b) of the firm. All variables are residualized against industry × country × year fixed effects and standardized. Only manufacturing firms are included.

4.2 Empirical specification

We use local projections (Jordà, 2005) to examine how financial frictions shape firms' responses to carbon prices. Our baseline specification is:

$$\Delta^h log(y_{j,t+h}) = \boldsymbol{\alpha_h} \boldsymbol{\Delta \widehat{log(CP_t)}} \times \boldsymbol{LC_{t-1}} + \sum_{l=1}^{2} \beta_h \Delta y_{j,t-l} \times LC_{t-1} + \sum_{l=1}^{2} \gamma_h \Delta y_{j,t-l} + \delta_h LC_{t-1} + \mu^h_{t,i(j),k(j)} + \epsilon_{j,t+h} \tag{1}$$

where $\Delta^h log(y_{j,t+h})$ represents the long difference $log(y_{j,t+h}) - log(y_{j,t-1})$ of the outcome variable for firm j. h indicates the yearly horizon, with $h = 0, ..., 3$. $\Delta log(CP_t)$ is the yearly change in the log of the average carbon price in year t. To restrict attention to exogenous variation in carbon prices, we instrument for $\Delta log(CP_t)$ with carbon price shocks (Känzig, 2023). LC_{t-1} is a dummy variable which takes the value of 1 if the firm is classified as facing low levels of financial constraints: if its net worth exceeds the 75th percentile of the net worth distribution within its industry, country, and year. $\mu_{t,i(j),k(j)}$ is a set of year-specific fixed effects for j's industry $i(j)$ and country $k(j)$. Standard errors are clustered at the time level (Almuzara and Sancibrián, 2024).

Our main coefficient of interest is α_h, which captures the cumulative differential percentage point response in the dependent variable y in year $t+h$ to a one percentage

point increase in the carbon price from $t-1$ to t if the firm is classified as facing low levels of financial constraints in $t-1$, relative to firms classified as facing high levels of financial constraints.

In order to test for the role of initial levels of productivity in influencing firm level responses to carbon price shocks, we expand our baseline local projections specification into a triple interactions specification with the following form:

$$\begin{aligned}\Delta log(y_{j,t+h}) = {} & \boldsymbol{\beta_h^1 \Delta \widehat{log(CP_t)} \times LC_{t-1} + \beta_h^2 \Delta \widehat{log(CP_t)} \times LC_{t-1} \times Prod_{t-1}} \\ & + \beta_h^3 \Delta \widehat{log(CP_t)} \times Prod_{t-1} + \sum_{l=1}^{2} \beta_h^4 \Delta y_{j,t-l} + \sum_{l=1}^{2} \beta_h^5 \Delta y_{j,t-l} \times LC_{t-1} \\ & + \sum_{l=1}^{2} \beta_h^6 \Delta y_{j,t-l} \times Prod_{t-1} + \sum_{l=1}^{2} \beta_h^7 \Delta y_{j,t-l} \times Prod_{t-1} \times LC_{t-1} + \beta_h^8 LC_{t-1} \\ & + \beta_h^9 Prod_{t-1} + \beta_h^{10} LC_{t-1} \times Prod_{t-1} + \mu_{t,i(j),k(j)}^h + \epsilon_{j,t+h}\end{aligned} \tag{2}$$

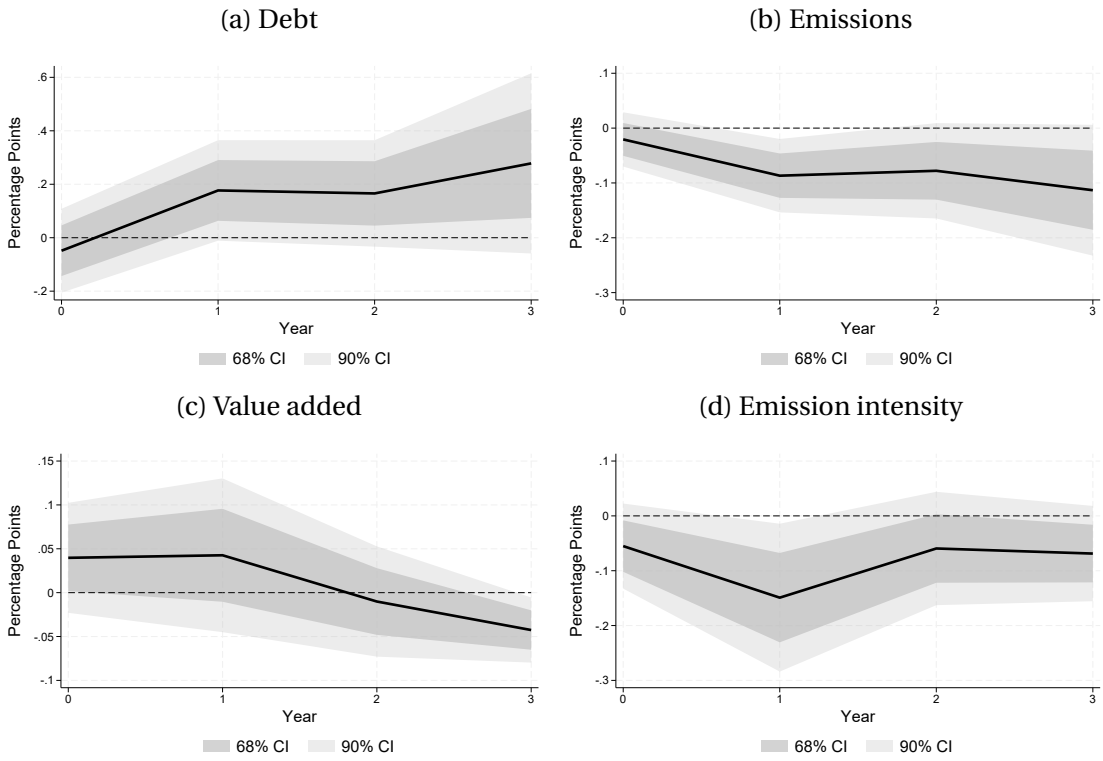
$Prod_{t-1}$ is a dummy variable which takes a value of 1 if the firm's productivity exceeds the median productivity in the same industry, country and year. From this specification, we have two main coefficients of interest. β_h^1 captures the cumulative differential percentage point response in the dependent variable y in year $t+h$ to a one percentage point increase in carbon prices from year $t-1$ to year t if the firm is classified as low constrained in $t-1$ relative to firms classified as more constrained, among low-productivity firms. $\beta_h^1 + \beta_h^2$ captures the differential cumulative impulse response among high-productivity firm.

4.3 Main results

The ability to access external finance appears to enable less constrained firms to differentially cut emissions in response to higher carbon prices (Figure 3). For each percentage point exogenous increase in the price of carbon, the following year less constrained firms increase borrowing by approximately 0.24% more than firms facing more binding financial constraints (panel a). Greater access to external finance seems to assist less constrained firms in reducing emissions by an additional 0.11% (panel b). The larger decline in emissions largely does not come at the expense of lower output, measured by value added (panel c), and thus leads to a relative decrease in emission intensities by 0.16% (panel d). The results suggest that firms rely on external finance to invest in improving environmental performance. While we do not observe a differential effect on

investments in tangible fixed assets (Figure A3), these investments could potentially be redirected towards greener capital vintages.[18]

Figure 3: Cumulative differential responses to carbon price shocks for less financially constrained firms

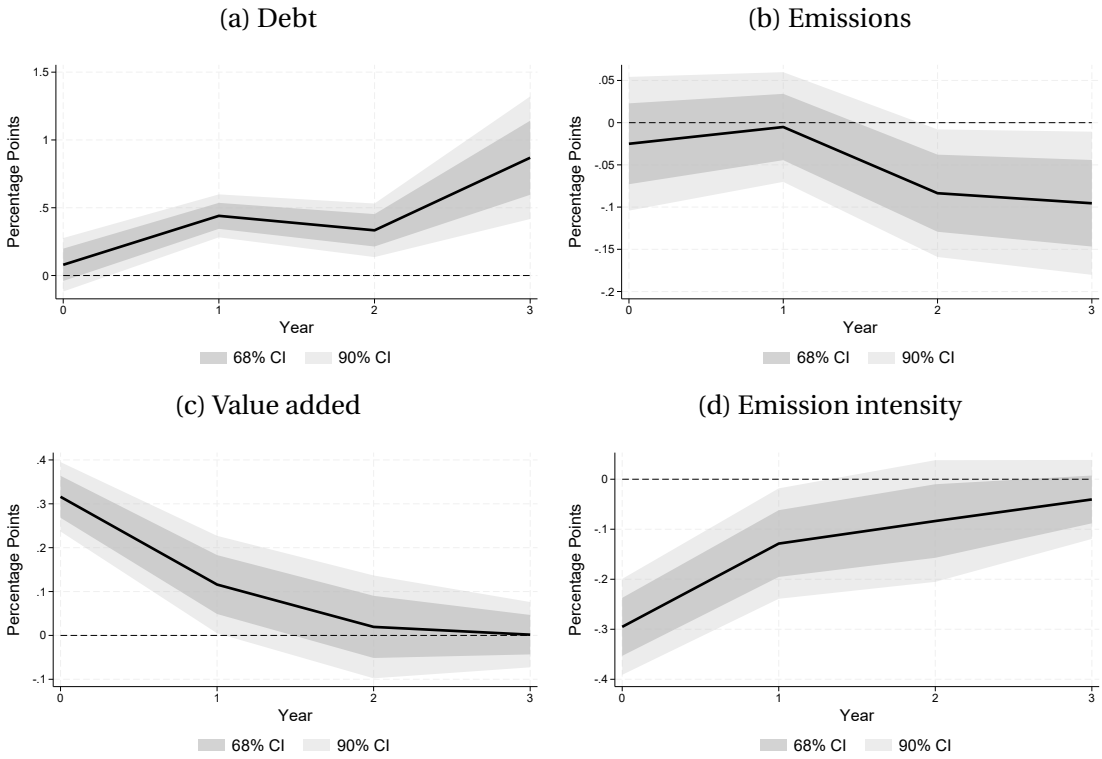


Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Better access to external finance seems to allow for differential environmental improvements in response to exogenously higher carbon prices to a larger extent within firms far from the productivity frontier (Figure 4 and Figure 5). Among low productivity firms, the less constrained relatively increase borrowing by 0.71% one year after a 1% exogenous rise in the carbon price. The differential increase rises to 1.29% two years later. Additionally, the less constrained are able to cut emissions by 0.10% more.

[18]The additional resources could also be utilized to implement other strategies which reduce emissions, such as process optimization or the adoption of sustainable practices.

Figure 4: Cumulative differential responses to carbon price shocks for less financially constrained firms, within less productive firms

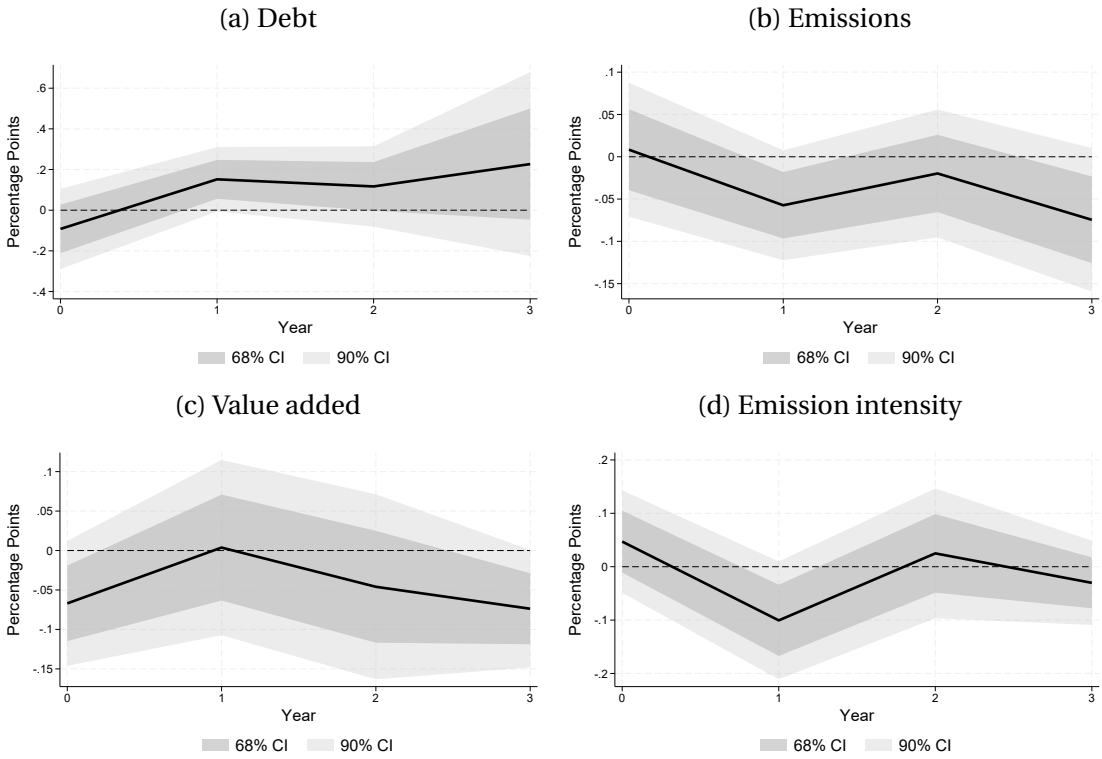


Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, separately for high and low productivity firms, estimated using Equation (2). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. A firm is classified as having high productivity if its productivity exceeds the median of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Higher access to external finance plays a smaller role in shaping firms' ability to adapt to higher carbon prices within firms with high productivity (Figure 5).

The results suggest the presence of a larger scope to reduce emissions for firms further from the productivity frontier. Firms relying on outdated machinery and production processes can simultaneously become greener and more productive by upgrading their capital equipment to newer vintages (Capelle et al., 2024). Those with higher access to financing are able to obtain the financial resources necessary to capitalize on this potential. Indeed, Figure A4 shows that only for firms with initial low levels of productivity, less constrained firms differentially increase their productivity in response

Figure 5: Cumulative differential responses to carbon price shocks for less financially constrained firms, within more productive firms



Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, separately for high and low productivity firms, estimated using Equation (2). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. A firm is classified as having high productivity if its productivity exceeds the median of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

to carbon price shocks.

4.4 Robustness

In this subsection we present robustness exercises of the results presented in Subsection 4.3. These additional results help address a range of concerns, including whether net worth accurately measures the degree of firm-level financial constraints and whether emissions reductions are driven by carbon leakage to other firms or installations.

Measuring financial constraints. Figure A5 and Figure A6 show that the differential results estimated using Equation (1) remain generally robust when utilizing leverage or size, respectively, instead of net worth to classify firms into facing low or high levels of financial constraints.[19]

Measuring productivity. One potential reason for variations in the productivity of firms is the vintage of capital stock that they use for production. Figure A7 and Figure A8 explore how the differential responses between firms facing low and high financial constraints differ for those with older and newer capital stocks, estimated using Equation (2). Consistent with splits by productivity, differential declines in emissions are larger for firms with older capital (Figure A7 panel b), and these firms see a differential increase in value added (panel d), resulting in a decrease in emission intensity (panel f).

Controlling for firm size. Firms with higher net worth are typically larger, and larger firms may respond differently to carbon shocks for reasons other than being less financially constrained. Figure A9 shows that results are robust to controlling for total firm assets.

Carbon leakage. Figure A10 provides evidence that the differential decline in emissions is not driven by carbon leakage to other firms, as there is no differential decline in the number of employees nor in material costs.

Carbon leakage may also occur within firms. We observe financial data at the firm level, encompassing all the installations owned by the firm. However, we only observe emissions for the installations covered by the EU ETS. If firms shift production from EU ETS-covered installations to those that are not covered, we would observe a decline in emissions while firm-level financials, such as value added, could remain unaffected. At the same time, firm-level unobserved emissions and emissions intensities may not fall. Figure A11 shows that results are robust to only including firms for which the number of recorded installations in Orbis does not exceed the number recorded under the EU ETS.

Additional robustness tests. Results are robust to using firm and year fixed effects (Figure A12), to clustering the standard errors at the firm and year level (Figure A13),

[19] A firm is classified as facing low levels of financial constraints if its leverage (total assets) is (are) below (above) the 25th (75th) percentile of the leverage (total assets) distribution within its industry, country, and year.

and to using robust standard errors (Figure A14).

5 A Model of Firm's Technological Adoption and Financial Frictions

In this section, we introduce a small open-economy heterogeneous-firm general equilibrium model in which firms make investment decisions and choose which capital vintage to use subject to a financial constraint. We use the model to interpret our empirical evidence and analyze its aggregate implications. We start with the description of the household sector, then the problem of the firm and close with the general equilibrium conditions.

5.1 Households

Time is continuous, indexed by t and runs to infinity. There is no aggregate uncertainty. There is a continuum of mass 1 of identical households indexed by $j \in [0,1]$. They have Greenwood–Hercowitz–Huffman (GHH) utility over consumption of final goods $c_j(t)$ and labor supply $\ell_j(t)$ (Greenwood et al., 1988):

$$u(c_j(t), \ell_j(t)) = \frac{1}{1-\psi_1}\left(c_j(t) - \psi_2 \frac{\ell_j(t)^{1+\psi_3}}{1+\psi_3}\right)^{1-\psi_1} \tag{3}$$

where ψ_1 is the inverse elasticity of intertemporal substitution and ψ_3 is the inverse Frish elasticity of labor supply.

Dropping the j-subscript, their objective is to maximize the integral of discounted utility, given by

$$U_t = \int_t^\infty e^{-\rho(\tau-t)} u(c(\tau), \ell(\tau))\, d\tau \tag{4}$$

where ρ is the discount rate.

Households face a budget constraint. Their earnings depend on their supply of labor to firms ℓ_t at a wage w_t per unit of time. They can also save in a risk-free bond b_t with instantaneous real rate of return r_t^*. Finally, they receive a transfer $\mathscr{D}_t$ from firms, which includes the dividends distributed by incumbent firms and the net worth of exiting

firms, net of the entry costs paid by starting firms, which we describe in more detail below. The households' financial wealth evolves as follows

$$\dot{b}_t = r_t^* b_t + w_t \ell_t - c_t + \mathscr{D}_t \tag{5}$$

where we normalize the price of final goods to 1.

Optimality conditions. The optimal intratemporal decision gives the following labor supply schedule

$$\ell_t = \left(\frac{w_t}{\psi_2}\right)^{\frac{1}{\psi_3}} \tag{6}$$

and the optimal intertemporal decision results in the following Euler equation

$$\frac{\dot{c}_t - \psi_2 \ell_t^{\psi_3} \dot{\ell}_t}{c_t - \psi_2 \frac{\ell_t^{1+\psi_3}}{1+\psi_3}} = \frac{1}{\psi_1}(r_t^* - \rho). \tag{7}$$

5.2 Final good producers

There is an endogenous mass μ_t of final good producers which supply a homogenous good to households at a price normalized to one. Firms are heterogeneous and characterized by two state variables: their total factor productivity z ("productivity" for short) and net worth a. Productivity is stochastic and evolves exogenously while net worth evolves endogenously. We denote $f_t(z,a)$ the mass of firms over these two state variables at time t. By definition, the integral of the mass of firms over the entire state space amounts to the total mass of firms in the economy $\int f_t(z,a)d(z,a) = \mu_t$.

Technology. Firms produce using a production function that combines capital k_v of vintage v, energy n and labor ℓ. The set of vintages, $\mathscr{V}_t$, has a countable number of elements bounded from below which follow an increasing order $v_0 < v_1 < v_2 ....$ The production function is given by

$$y = z\left(v \min(k_v, \eta n)\right)^{\kappa} \ell^{\lambda} \tag{8}$$

where (log) productivity $\log(z)$ follows an Ornstein-Uhlenbeck process:

$$d\log(z) = \mu(z)dt + \sigma_z dW_t \tag{9}$$

$$\text{with} \quad \mu(z) = \theta(E(\log(z)) - \log(z)) \tag{10}$$

where dW_t is a Brownian motion, θ governs the degree of productivity mean reversion, $\mu(z)$ its deterministic drift, and σ_z its dispersion.

Capital of a given vintage and energy are perfect complements ("Leontief"): the amount of energy required to operate capital k_v of vintage v is given by k_v/η and is thus allowed to vary with each vintage. We assume that more productive vintages are weakly more energy-efficient $v' > v \Rightarrow \eta_{v'} \geq \eta_v$.

In addition, firms emit greenhouse gases. Following Capelle et al. (2024), the production function of emissions is given by

$$e = \phi v^{-\gamma} n \tag{11}$$

where ϕ parametrizes the average emission per unit of energy consumption in the economy. Equation (11) captures the idea that more productive vintages are more emission-efficient for a given level of energy consumption, consistent with empirical evidence (Capelle et al., 2024).

Firms need to purchase their stock of capital of a given vintage at a price q_{vt} which depends on the quality of the vintage. Intuitively, more productive and newer vintages are more expensive $v < v' \Rightarrow q_{vt} < q_{v't}$, otherwise no firm would use the older ones. Firms fund their capital investment with a mix of equity a and debt b:

$$q_{vt}k_v = a + b. \tag{12}$$

Importantly, firms face two external financing constraints. First they cannot obtain external equity finance, which means that a can only be increased through retained earnings. Second they are subject to a leverage limit

$$q_{vt}k_v \leq \chi a \tag{13}$$

where $\chi \geq 1$ is an exogenous parameter. When $\chi = 1$ firms need to self-finance. On the contrary, when $\chi \to +\infty$ capital markets are perfect. This constraint is a common

feature of models with moral hazard and limited commitment and captures the fact that, to ensure a certain minimum skin in the game, the amount of capital available to a firm is limited by its equity.

Firms' objectives and net worth accumulation. Firms maximize the discounted sum of future dividends $\int_t^{+\infty} e^{-r_\tau^* \tau} d_\tau d\tau$. Dividends are distributed in a lump-sum fashion to households. When a firm exits, its equity is transferred to households in a lump sum fashion. Firms choose the path of dividends d_t to maximize the value of the firm. They trade off paying dividends in the present against using the resources to accumulate net worth, which can lead to higher dividends in the future.

The law of motion of net worth is given by

$$\dot{a} = r_t^* a + \pi_t(z,a) - d_t. \tag{14}$$

where $\pi_t(z,a)$ is the equilibrium profit of a firm with productivity z and net worth a. The term $r_t^* a$ corresponds to the share of the cost of capital that is self-financed, which allows the firm to save on interest charges to lenders (see below for a derivation).

In recursive form, the value function of a firm with productivity z and net worth a is the solution to the following Hamilton-Jacobi-Bellman (HJB) equation

$$\rho V_t(z,a) = \max_d d + \frac{\partial V}{\partial a}(r_t^* a_t + \pi_{it}(z,a) - d) + \mu(z)\frac{\partial V}{\partial z} + \frac{\sigma^2}{2}\frac{\partial^2 V}{\partial z^2} + \frac{\partial V}{\partial t} \tag{15}$$

where the term in $\frac{\partial V}{\partial a}$ corresponds to the deterministic drift in net worth, $\frac{\partial V}{\partial z}$ to the deterministic drift in TFP, $\frac{\partial^2 V}{\partial z^2}$ to the volatility of TFP and $\frac{\partial V}{\partial t}$ to deterministic aggregate changes in prices and taxes.

Profit maximization. Firms make four decisions regarding their inputs. They choose how much labor to hire, how much energy to use, how much capital to use and whether to adopt a newer capital vintage.

Firms are competitive. They take the prices of the homogeneous final good and their inputs—the wage w_t, the price of energy m_t, the price of carbon τ_t, the price of capital vintages q_{vt}, and the user cost of capital vintages r_{vt}—as given. The user cost of

capital is the key determinant of the optimal choice of capital. It is given by

$$r_{\nu t} = q_{\nu t}\left(r^* + \delta - \frac{\dot{q}_{\nu t}}{q_{\nu t}}\right). \tag{16}$$

where r^* is the interest rate, δ the rate of depreciation and $\frac{\dot{q}_{\nu t}}{q_{\nu t}}$ is the rate of change of capital prices.

To see where this expression comes from, consider a firm investing in capital $k_{\nu t}$ for a small time interval dt. It has to purchase the capital $q_{t\nu}k_{\nu t}$, then it has to pay the interest rate r^* to the lenders for the amount of debt $q_{t\nu}k_{\nu t} - a$, then it can resell the undepreciated capital stock with a value $q_{\nu t+dt}k_{\nu t}$. Taken together:

$$\begin{aligned} & q_{t\nu}k_{\nu t} + r^* \times dt \times (q_{\nu t}k_{\nu t} - a) - (1 - \delta \times dt) \times q_{\nu t+dt} \times k_{\nu t} \\ \text{which gives} \quad & k_{\nu t}\left(dt \times q_{\nu t} \times \left(r^* + \frac{q_{\nu t+dt}}{q_{\nu t}} \times \delta\right) - (q_{\nu t+dt} - q_{\nu t})\right) - r^* \times dt \times a \end{aligned}$$

Dividing by dt and taking the limit $dt \to 0$, we obtain $q_{\nu t}k_{\nu t}\left(r^* + \delta - \dot{q}_{\nu t}/q_{\nu t}\right) - r^* a$. The first term corresponds to the user cost of capital, and the second corresponds to the interest charges saved on the share of the capital funded with net worth.

At each instant, the firm problem is given by

$$\pi_{it}(a,z) = \max_{\nu,k_\nu,\ell,n} y - w_t\ell - m_t n - \tau_t e - r_{\nu t}k_\nu \tag{17}$$

$$y = z\left(\upsilon \min(k_\nu, \eta n)\right)^\kappa \ell^\lambda \tag{18}$$

$$q_{\nu t}k_\nu \leq \chi a, \tag{19}$$

where we normalize the price of the final good to 1.

5.3 Entry and Exit

We assume that firms die randomly at rate ζ per unit of time. When they die, their net worth is transferred to households in a lump-sum fashion.

There are also potential entrepreneurs who can start a company with net worth $\underline{a}$ after paying a fixed cost κ_e in terms of the final good and before learning about their productivity draw $z \sim H(z)$. $H(.)$ denotes the cdf of the distribution, where $h(.)$ is the pdf. We assume that the flow of entrants at time t, p_t, is a function of the profit opportunities

going forward, i.e.,

$$p_t = p_\infty \exp\left\{\xi\left(\int_z v_t(\underline{a}, z)\, dH(z) - \kappa_e\right)\right\} \tag{20}$$

with $\xi > 0$ and p_∞ is the entry rate in the final steady state. The case with $\xi \to +\infty$ corresponds to the traditional free entry condition, given by

$$\int_z v_t(\underline{a}, z)\, dH(z) = \kappa_e. \tag{21}$$

Our more general specification for firm entry, Equation (20), is more numerically stable and gives rise to a meaningful transition path.

5.4 Capital goods producers

A set of competitive capital good producers transform final goods into capital goods, which they sell to and buy from final goods firms, using a linear technology.

$$i_v = \iota_{vt} y \tag{22}$$

where the productivity ι_{vt} is allowed to be vintage-specific, reflecting the fact that some vintages are more costly to produce than others. It is also allowed to be time-specific, which will be a key driver of the transition to a lower-carbon steady-state in absence of policies.

At the aggregate level, the quantity of capital of each vintage follows the law of motion of capital:

$$\dot{K}_{vt} = -\delta K_{vt} + i_{vt} \tag{23}$$

5.5 Market Clearing, Resource Constraint and Equilibrium

We consider a small-open economy which trades goods and risk-free bonds freely with the rest of the world. Labor is not tradable, and thus the labor market has to clear domestically. Denoting labor supply of household j at time t as ℓ^s_{jt} and $\ell_t(z,a)$ the labor demand of a firm with productivity z and net worth a, the labor market clearing

condition is given by

$$\int \ell_{jt}^{s} dj = \int \ell_t(z,a) dF(z,a) \tag{24}$$

Although the goods market does not need to clear domestically, it is still useful to consider the resource constraint of the economy:

$$Y_t = \int c_t(j) dj + I_t + NX_t \tag{25}$$

$$I_t = \sum_{v} \iota_{vt}^{-1} (\dot{K}_{vt} + \delta K_{vt}) + p_t \kappa_e \tag{26}$$

where NX_t denotes net exports.

Consistent with our application to Europe, we assume that firms import energy from the rest of the world at an exogenous price m.

Finally, the equilibrium mass function $f(z,a)$ (with cdf denoted $F(z,a)$) is consistent with the law of motion of net worth at the firm-level, the death process and the entry decision of potential entrepreneurs. The following Kolmogorov-forward equation describes this law of motion

$$\frac{\partial f(z,a)}{\partial t} = -\zeta f(z,a) - \frac{\partial}{\partial a}[f(z,a)(r_t^* a_t + \pi(z,a) - d(z,a))] \tag{27}$$

$$+ \mathbb{1}_{a=0} p_t h(z) - \frac{\partial}{\partial z}[\mu(z) f(z,a)] + \frac{\partial}{\partial z^2}[\sigma^2 f(z,a)] \tag{28}$$

where p_t is the flow of entrants at time t.

The equilibrium definition is standard. An equilibrium is a path of consumption c_t, labor supply ℓ_t^s, bond holdings b_t, transfers $\mathscr{D}_t$, firm policy rules for labor demand $\ell(z,a)$, capital of each vintage v $k_{vt}(a,z)$, a vintage choice $v(a,z)$, energy consumption $n(z,a)$, dividends $d(z,a)$, value function $V(z,a)$, firms distribution $f_t(z,a)$, flow of entrants p_t and wages w_t such that

- Given prices, c_t and ℓ_t^s maximize the households' utility subject to their budget constraint.

- Given prices, $\ell(z,a)$, $k_{vt}(a,z)$, $v(a,z)$, $d(z,a)$ maximize the firm's value function subject to the financial constraint and the value is the solution to the HJB equation (15).

- The labor market clears, free entry holds and the distribution of firms is consistent with the Kolmogorov-forward equation (28).

6 Equilibrium Properties and Pecking Order of Vintages

This section has three goals. First, we derive firms' optimal static and dynamic decisions. Second, we explain the central trade-off between vintage quality and the scale of their investment in capital faced by a firm that is financially constrained. Third we derived the key result of this section: firms' vintage adoption follows a pecking order. Details on the derivations can be found in Appendix A2.

6.1 Firm's optimal energy, labor and capital decisions

Investment good firms. We begin with the optimality conditions for firms producing investment goods. Given that their technology is linear and they are competitive, prices of investment goods are pinned down by the inverse of the productivity parameter:

$$q_{vt} = \iota_{vt}^{-1} \tag{29}$$

and they make zero profit in equilibrium.

Final good firms - labor and energy. We now turn to the final good firms. We start with their choice of energy and labor. Given our Leontief assumption, the optimal level of energy consumption is the ratio of the stock of capital over the energy efficiency of its vintage:

$$n = \frac{k_v}{\eta}. \tag{30}$$

The optimal choice of labor is given by the traditional equalization of marginal product of capital with its marginal cost, which combined with the Cobb-Douglas production technology gives the following expression

$$\ell = \lambda \frac{y}{w_t}. \tag{31}$$

Final good firms - capital, output and profits. The optimal choice of capital depends on whether the firm hits the financial constraint. Denote Λ the Lagrange multiplier associated with the financial constraint (19). The first order condition for capital is given by

$$\kappa \frac{y}{k} = r_{vt}\left(1 + \Lambda\left(r^* + \delta - \frac{\dot{q}_{vt}}{q_{vt}}\right)^{-1}\right) + \frac{m_t + \tau_t v^{-\gamma}}{\eta} \tag{32}$$

When the financial constraint is binding, the marginal product of capital $\kappa y/k$ is higher than its marginal cost $r_{vt} + \frac{m_t+\tau_t v^{-\gamma}}{\eta}$ as the firm cannot be as capital-intensive as it would like to be.

Lemma 1 (Constrained Capital, Output and Profits)**.** *Assume the firm is financially constrained and uses vintage v. Its capital stock is given by $k_v = \frac{\chi a_t}{q_{vt}}$, and output and profits by*

$$y = \left[z\left(v\frac{\chi a_t}{q_{vt}}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right]^{\frac{1}{1-\lambda}} \tag{33}$$

$$\pi_t = \left[z\left(v\frac{\chi a_t}{q_{vt}}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right]^{\frac{1}{1-\lambda}}[1-\lambda] - \chi a_t\left(r^* + \delta - \frac{\dot{q}_{vt}}{q_{vt}} + \frac{m_t + \tau_t v^{-\gamma}}{\eta q_{vt}}\right) \tag{34}$$

If the firm has a high enough level of net worth, it is unconstrained. In that case, the Lagrange multiplier in equation (32) is equal to 0 and we can derive the optimal output and capital by substituting this equation into the production function.

Lemma 2 (Unconstrained Capital, Output and Profits)**.** *Assume the firm is financially unconstrained and uses vintage v. The optimal level of capital is given by*

$$k_v = \frac{\kappa}{r_{vt} + \frac{m_t+\tau_t v^{-\gamma}}{\eta}}\left(z\left(v\frac{\kappa}{r_{vt} + \frac{m_t+\tau_t v^{-\gamma}}{\eta}}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right)^{\frac{1}{1-\kappa-\lambda}} \tag{35}$$

with $\kappa + \lambda < 1$. Output is given by

$$y = \left(z\left(v\frac{\kappa}{r_{vt} + \frac{m_t+\tau_t v^{-\gamma}}{\eta}}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right)^{\frac{1}{1-\kappa-\lambda}} \tag{36}$$

and profits are given by

$$\pi_t(v,z) = \left(z \left(v \frac{\kappa}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta}} \right)^{\kappa} \left(\frac{\lambda}{w_t} \right)^{\lambda} \right)^{\frac{1}{1-\kappa-\lambda}} [1-\lambda-\kappa]. \tag{37}$$

6.2 The trade-off between scaling up capital investment and adopting a higher-quality vintage

Unconstrained firms. We start with looking at the case of an unconstrained firm. Taking the log of profits and keeping only the term that depends on v, the optimal vintage in this case is the one that maximizes the following expression

$$\log \left(\frac{v}{q_v} \frac{1}{\left(r^* + \delta - \frac{\dot{q}_{vt}}{q_{vt}} \right) + \frac{m_t + \tau_t v^{-\gamma}}{\eta q_v}} \right) \tag{38}$$

Several elements determine the optimal vintage of unconstrained firms. On the one hand, firms prefer vintages with higher productivity v, and vintages that are emission- and energy-efficient $(v^{-\gamma}, \eta)$ to save on carbon taxes and energy cost. On the other hand, they may be disincentivized from buying newer vintages due to higher prices, q_v. Finally, firms prefer vintages whose price will not shrink in the short run $\frac{\dot{q}_{vt}}{q_{vt}}$ to avoid capital losses.

The optimal vintage choice trades off these different forces. The choice of vintage that maximizes the objective (38) is independent of the firm's characteristics, including its productivity. We impose some regularity conditions to ensure that an interior optimal vintage exists.

Assumption 1. *Define* $T(v) = \log \left(\iota_{vt} v \frac{1}{\left(r^* + \delta + \frac{\dot{\iota}_{vt}}{\iota_{vt}} \right) + \iota_{vt} \frac{m_t + \tau_t v^{-\gamma}}{\eta}} \right)$. *$T(v)$ is continuous, first strictly increasing then strictly decreasing.*

These assumptions mean that for low v, increases in v result in energy- and emission-efficiency gains $(v^{-\gamma}, \eta)$ that outweigh price increases $q_v = \iota_{vt}^{-1}$. The reverse is true for sufficiently large values of v. A necessary condition for this assumption to hold is that the term $v/q_v = v\iota_{vt}$—the inverse of the cost of more productive vintages relative to their productivity—decreases at least for high enough values of v, given that the other

term $\frac{1}{\left(r^*+\delta+\frac{\dot{\iota}_{vt}}{\iota_{vt}}\right)+\frac{m_t+\tau_t v^{-\gamma}}{\eta q_v}}$ is increasing in v. A direct implication of these assumptions is that there exists a unique optimal vintage v^* common to all firms.

Lemma 3. *Under assumption 1, there exists a unique v^* such that $\pi_t^U(v^*,z) \geq \pi_t^U(v,z)$ for all v and all z.*

The optimal vintage depends only on the price of energy m_t, the interest rate r^*, the carbon tax τ, and the productivity of the capital production technology $\{\iota_v\}_v$.

Constrained firms. We now derive the optimal choice of v when the firm is financially constrained. Unlike financially unconstrained firms, the optimal vintage decision of a constrained firm considers the fact that the choice of vintage affects the maximum amount of capital that the firm can invest in through the financial constraint. This effect is all the more relevant when the firm is far from its optimal level of capital. To see this, consider a firm with productivity z and net worth a that contemplates the difference in profits between two consecutive vintages $v < v'$:

$$\left[z(\chi a_t)^\kappa \left(\frac{\lambda}{w_t}\right)^\lambda\right]^{\frac{1}{1-\lambda}} [1-\lambda]\left[\left(\frac{v'}{q_{v't}}\right)^{\frac{\kappa}{1-\lambda}} - \left(\frac{v}{q_{vt}}\right)^{\frac{\kappa}{1-\lambda}}\right] - \chi a_t\left(\frac{m_t+\tau_t(v')^{-\gamma}}{\eta_{v'}q_{v'}} - \frac{\dot{q}_{v't}}{q_{v't}} - \frac{m_t+\tau_t v^{-\gamma}}{\eta q_v} + \frac{\dot{q}_{vt}}{q_{vt}}\right) \tag{39}$$

Each line corresponds to one distinct side of the trade-off between vintage quality and the scale of investment in capital that financially constrained firms face. Let's start with the vintage quality side of the trade-off. It is captured by the second line $\left(\frac{m_t+\tau_t(v')^{-\gamma}}{\eta_{v'}q_{v'}} - \frac{\dot{q}_{v't}}{q_{v't}} - \frac{m_t+\tau_t v^{-\gamma}}{\eta q_v} + \frac{\dot{q}_{vt}}{q_{vt}}\right)$. Assuming that the price of vintages is constant over time $\dot{q}_v = \dot{q}_{v'} = 0$, this term is always negative, because more productive vintages are more energy- and emission-efficient. This force pushes firms to adopt more productive vintages because they can save on costs.

On the other hand, more productive vintages are also more expensive, and they force firms with limited ability to leverage to buy less capital to stay within their constraint. In turn, this lowers their output and eventually their profits given that the firm is below its optimal level of capital. This second force is captured by the first line, and for it to hold however, the term $\left[\left(\frac{v'}{q_{v't}}\right)^{\frac{\kappa}{1-\lambda}} - \left(\frac{v}{q_{vt}}\right)^{\frac{\kappa}{1-\lambda}}\right] < 0$ needs to be negative. If it were positive, then the most productive vintage (highest v) would always be strictly preferred for

any level of wealth a. For this term to be negative, in turn, the productivity-price ratio should decrease with v, $v'/q_{v'} < v/q_v$, i.e., the cost of more productive vintages grows quicker than their productivity, consistent with assumption 2.

Assumption 2. *Consider any pair of consecutive vintages $v < v'$. Then*

$$\iota_v v > \iota_{v'} v' \tag{40}$$

6.3 A pecking order of vintages

We now show that this assumption gives rise to a pecking order of vintages in the sense that as firms grow and accumulate net worth they switch to more productive vintages until they settle on the most productive one v^*. Rewriting Equation (39) and dividing by χa_t gives

$$\begin{aligned}&\left(\frac{m_t+\tau_t(v')^{-\gamma}}{\eta_{v'}q_{v'}}-\frac{\dot{q}_{v't}}{q_{v't}}-\frac{m_t+\tau_t v^{-\gamma}}{\eta q_v}+\frac{\dot{q}_{vt}}{q_{vt}}\right)\\&-(\chi a_t)^{\frac{\kappa}{1-\lambda}-1}\left[z\left(\frac{\lambda}{w_t}\right)^{\lambda}\right]^{\frac{1}{1-\lambda}}[1-\lambda]\left[\left(\frac{v}{q_{vt}}\right)^{\frac{\kappa}{1-\lambda}}-\left(\frac{v'}{q_{v't}}\right)^{\frac{\kappa}{1-\lambda}}\right]\end{aligned} \tag{41}$$

Assuming that the real price of vintages remains constant over time $\frac{\dot{q}_{v't}}{q_{v't}} = \frac{\dot{q}_{vt}}{q_{vt}} = 0$, the second line is continuous and strictly decreasing with a_t, it goes to infinity as a approaches zero and to 0 as a goes infinity. This equation thus defines a threshold $\bar{a}_v$ at which a firm is indifferent between v and v', as formalized in the following lemma.

Lemma 4. *Assume $\kappa+\lambda<1$ and $\dot{q}_{vt}=0$ for all v and $\iota_v v > \iota_{v'} v'$ for any consecutive pair $v<v'$ then for any t, z and any pair of consecutive vintages $v<v'$, there exists $\bar{a}_t(z,v)>0$ such that*

$$a \leq \bar{a}_t(z,v) \iff \pi_t^C(z,a,v) \geq \pi_t^C(z,a,v') \tag{42}$$

That is, for net worth values lower than the threshold $\bar{a}_t(z,v)$, it is more profitable for the firm to utilize the lower productivity vintage v for production.

The net worth threshold $\bar{a}_t(z,v)$ depends on the firm's productivity type z. Firms with lower z have a lower threshold of adopting a given vintage, i.e., $z<z' \Rightarrow \bar{a}_t(z,v) < \bar{a}_t(z',v)$. This is because firms with lower productivity have a smaller optimal level of capital, so they face weaker incentives to distort their vintage decision to get bigger.

The thresholds of net worth also depend on time through changes in wages and capital goods prices. Importantly, increases in wages lower all thresholds such that firms adopt a given vintage at lower levels of net worth. The intuition is that when wages increase, firms' optimal size and thus level of capital decrease, which alleviates the cost of the borrowing constraint.

The previous results lead to the following proposition which says that there is a pecking order of vintages through which firms move as they grow and accumulate net worth, until they settle on the most productive vintage v^*.

Proposition 1 (Pecking order of vintages.)**.** *Under the same assumptions as lemma 4, for any z and t, there exists a strictly increasing sequence $\bar{a}_t(z,v_0) < \bar{a}_t(z,v_1) .... < \bar{a}_t(z,v^*)$ such that a firm uses vintage $v \leq v^*$ if and only if $a \in [\bar{a}_t(z,v), \bar{a}_t(z,v')]$.*

7 Calibration

We now calibrate the model to match important moments of the empirical distribution of firms' sizes and productivity, the green bias of capital-embedded technologies, the firms' energy consumption and the average leverage of firms in Europe.[20] A subset of the parameters are calibrated externally. The rest are estimated from the data.

7.1 External calibration

We begin by calibrating a number of parameters that can be set externally. These parameters are listed in Table 1. The time discount factor ρ and the depreciation rate of physical capital δ are calibrated to standard values used in the literature, 4 and 5% respectively. Similarly, the interest rate is set to 4%.

We then put more structure on the productivity-price change over vintages. We assume that the rate of improvement of productivity v across vintages is constant and denoted g_v. We also assume that there exists $u < 1$ such that

$$\iota_{v't} v' = u \iota_{vt} v \tag{43}$$

We set the value for the growth rate of vintage productivity to 11.9%, which is close to values used in the literature analyzing the contribution of improvements in capital

[20] Footnote 1 describes the list of countries participating in the ETS.

goods to long-run growth (Greenwood et al., 1997).

Calibrating the growth rate of vintage prices relative to their productivity, u, is challenging because data on vintage prices is scarce. Given this limitation, we set it to .9 which corresponds to a 10% increase across two consecutive vintages one year apart.

Table 1: Externally calibrated parameters

Parameter	Description	Value	Source
ρ	Discount rate	0.04	Standard
δ	Depreciation rate of capital	0.05	Standard
r	Interest rate	4%	Standard
g_v	Growth rate of vintage productivity	11.9%	Capelle et al. (2024)
$g_v - g_p = \log(u)$	Vintage productivity/price growth	.9	Benchmark
γ	Emissions elasticity to vintage	0.27	Capelle et al. (2024)
λ	Labor elasticity of output	0.64	Ottonello and Winberry (2024)
ψ_3	Wage elasticity of labor	2.5	Standard (See notes)
m	Price of energy	1	Normalization
ξ	Elasticity of entry	.1	Gutiérrez and Philippon (2019)
θ	Mean reversion of $\log(z)$	.1	Asker et al. (2014)
τ	Price of carbon	30	ETS and authors' calculations

Notes: Macroeconomic estimates of the Frisch elasticity generally range between values of 1 to 4 (Smets and Wouters, 2007; Hall, 2009; Rogerson and Wallenius, 2009; Keane and Rogerson, 2012; Mui and Schoefer, 2024).

For the elasticity of emissions to vintages, γ, we follow the empirical estimate provided by Capelle et al. (2024). To account for a different scaling of vintages, v, we multiply their elasticity (.036) by the ratio of the standard deviation of vintages in their data (1.11) and in our model (.15), which gives $\gamma = .27$.

For the elasticity of output to labor, we follow Ottonello and Winberry (2024) and set it to $\lambda = .64$, which is also consistent with the labor share in Europe. The energy intensity is normalized to 1. The wage elasticity of labor is set to 2.5, within the range used in the literature (Smets and Wouters, 2007; Hall, 2009; Rogerson and Wallenius, 2009; Keane and Rogerson, 2012; Mui and Schoefer, 2024). To calibrate the elasticity of entry to profit opportunities—a parameter that matters for the speed of the transition—we follow Gutiérrez and Philippon (2019) who estimate that in the recent decades it has been around .1. The mean reversion of firm TFP is set to .1 consistent with empirical estimates at the firm-level in European countries (Asker et al., 2014).

We calibrate the price of a ton of carbon in the ETS market to its level before the pandemic, at about €30 a ton.

7.2 Internal Calibration

Other model parameters are estimated to match empirical moments of the distribution of firms' input and output. Table 2 gives the full list.

We briefly summarize our calibration strategy here. Although no single moment pins down one parameter, we explain which moment is most informative about which parameter. The cost of entry parameter κ_e is tightly connected to the cost of entry relative to GDP in the data. The parameter is set to .185, which results in an entry cost of 3.4% of annual income per capita, the cost of starting a new business in Europe according to the World Bank.[21] The exit rate in the data is directly connected to the probability of exit in the model.[22] The energy efficiency of vintages η is disciplined

Table 2: Internally calibrated parameters

Parameter	Description	Value
κ_e	Cost of entry	.185
ζ	Exit rate	.025
η	Energy efficiency of vintages	35
ϕ	Average emissions per unit of energy	.015
σ_z	Dispersion of productivity	.206
κ	Capital elasticity of output	.1375
χ	Maximum leverage ratio	2.2
ψ_2	Labor preference parameter	2.7645

by the share of cost spent on energy, which is around 5% of total costs.[23] The average emissions per unit of energy (in tons per gigajoule) is informative about ϕ, the scale parameter in the firms' emissions technology.

The standard deviation of the productivity process σ_z is directly related to the firm size variance in the data. The covariance of output and TFP directly informs the elasticity of output to capital κ. The leverage constraint parameter χ has a first-order effect on the average leverage of corporations, which is about 33% in the data.[24] Finally, the labor preference parameter ψ_2 is set to be consistent with a labor supply normalized to $\ell = \left(\frac{w}{\psi_2}\right)^{1/\psi_3} = 1$.

[21] Data on entry cost can be found here.
[22] Data on exit rate can be found here.
[23] Data on energy cost can be found here.
[24] Data on firms' leverage can be found here.

7.3 Model Fit and Validation

Table 3 shows that the model performs well in matching the targeted aggregate and distributional moments.

Table 3: Targeted moments

Moments	Data	Model	Source
Cost of entry relative to GDP	3.4%	4.2%	World Bank (WDI)
Exit rate	2.5%	2.5%	Eurostat
Energy cost (% of total cost)	3.1%	2.9%	Eurostat
Average emissions per unit of energy	.06	.06	Orbis, ETS, own calculations
Firm size variance	2.66	2.56	Orbis, own calculations
Covariance of output and TFP	.57	.57	Orbis, own calculations
Average leverage of corporations	35%	35%	Eurostat

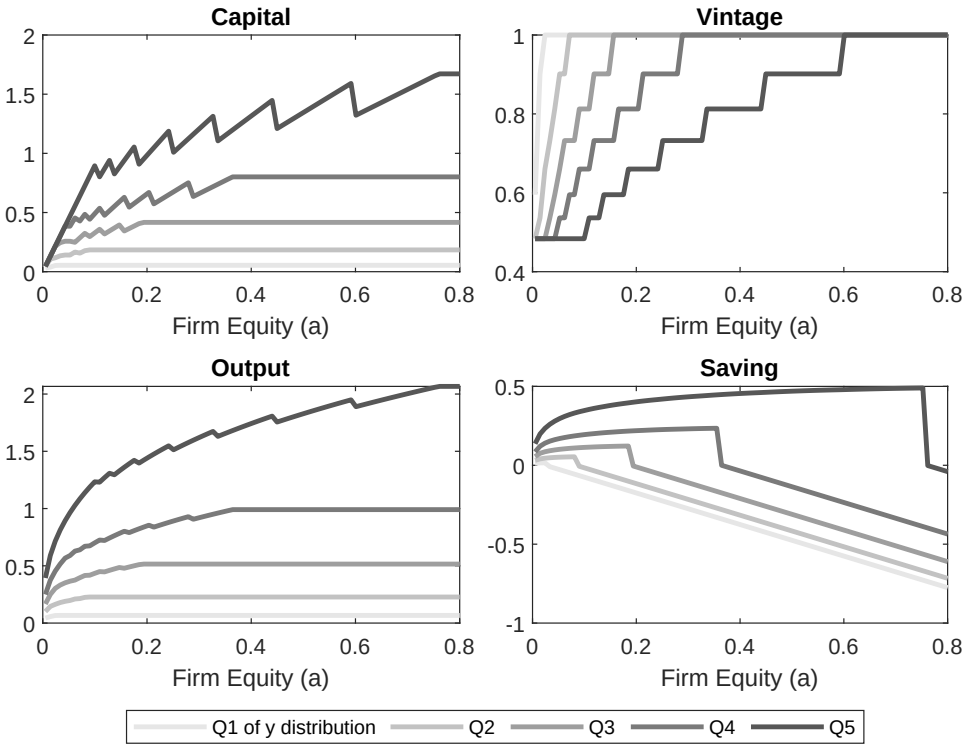
Figure 6 shows the equilibrium policy rules for the capital stock k, the quality of the vintage v, total output and the level of saving by firms as a function of their net worth a for five different quantiles of the productivity z-distribution.[25] Consistent with the theoretical insight developed in proposition 1, there is a pecking order of vintages: given an exogenous productivity z, lower-net-worth firms adopt worse vintages and they upgrade to better vintages as they grow and accumulate savings. This strategy is optimal because it allows them to buy more capital and get closer to their optimal scale while they are still financially constrained. The fact that the size of the capital stock and output shrinks when firms upgrade shows the trade-off between vintage quality and the scale of investment in capital that financially-constrained firms face.

Figure 7 shows the equilibrium distributions of net worth a, exogenous productivity z, output y and emissions e. While we target only the variance of the distribution of sizes y, these distributions look broadly consistent with their empirical counterpart.

In addition, we now present a test of the model's validity and consistency with the empirical evidence presented above. More specifically, we compare the empirical estimates of the differential causal effect of a carbon price shock across more and less financially constrained firms to the model's predictions. We compute the model-generated response of the economy to a carbon price increase across firms with net worth above the 75th and below the 25th percentile of the distribution of net worth,

[25] Given that the distribution of firm size is highly skewed, we select the quantiles so that each quantile accounts for 20% of aggregate output.

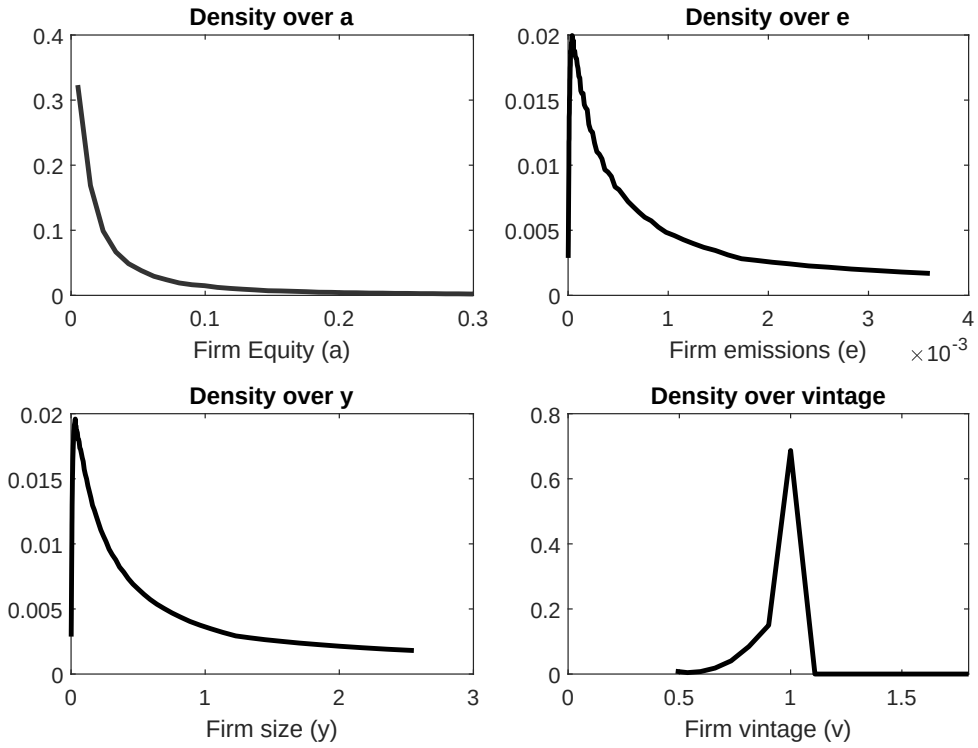
Figure 6: Policy rules: baseline steady state



Notes: This graph shows the policy rules in the market equilibrium for the optimal scale of capital investment (top left), vintage quality (top right), output (bottom left) and saving (bottom right). The x-axis is the firm equity (a). Different shades of gray correspond to different values of firm TFP z. The values of z are the quintiles of the cumulative distribution of firms output.

as in the empirical exercise. The shock is calibrated to match the expected increase in carbon prices over the next decade from $\tau = 30$ to $\tau = 100$, to facilitate the comparison with our main exercise in Section 8. We find that firms with higher net worth reduce their emissions and their emissions intensity more strongly than firms with lower net worth. Qualitatively, this result is consistent with the empirical differential response to a carbon price shock in Section 4. Quantitatively, we find that the cumulative differential response of emissions to a one log point increase in the price of carbon is equal to .05 log points. This is of the same order of magnitude as the empirical estimates (.1 log point).

Figure 7: Equilibrium distributions of net worth, emissions, output and vintages



Notes: This graph shows the equilibrium densities in the market equilibrium over net worth (top left), emissions (top right), output (bottom left) and vintages (bottom right).

8 Quantitative Results on the Role of Financial Frictions

In this section, we use the calibrated model to analyze how financial frictions shape aggregate emissions and the effectiveness of mitigation policies. We first look at an extreme counterfactual where we remove all financial frictions. We then simulate an increase in the price of carbon, and analyze how financial frictions affect its cost in terms of output and its effectiveness in reducing emissions. We finally assess whether financial policies that are biased towards green investments could help with mitigation objectives.

8.1 The Role of Financial Frictions

Our first counterfactual consists in removing financial frictions altogether by lifting $\chi \to +\infty$ while keeping the carbon price unchanged at its baseline level. The goal of the exercise is to isolate the effects of financial frictions on aggregate emissions and output, and to study the mechanisms through which they operate.

Qualitatively, the effect on emissions is ambiguous and depends on the interplay of different opposing channels. On one hand, financial constraints make it difficult for firms to adopt greener, more efficient, but more expensive technologies, as highlighted in the previous sections. On the other hand, financial frictions lower the average scale of production and tilt the optimal input mix away from capital which is complementary to energy use. The first effect implies that financial constraints could increase emissions while the latter two go in the opposite direction.

To quantify these different channels, we decompose the change in aggregate emissions E in three terms as shown in formula (44) below. The first term is the change in average emissions per unit of energy $\frac{e(z,a)}{n(z,a)}$, which isolates the first channel; the second is the change in energy consumption per unit of output $\frac{n(z,a)}{y(z,a)}$, which isolates the second channel; the third includes all other factors, encompassing changes in output $y(z,a)$ and in the distribution of firms $dF(z,a)$.

$$E = \int e(z,a)dF(z,a) = \int \frac{e(z,a)}{n(z,a)} \frac{n(z,a)}{y(z,a)} y(z,a)dF(z,a). \tag{44}$$

Table 4 shows the values of several important macroeconomic variables in the steady-state equilibrium of our economy in the baseline (column 1) and in the counterfactual in which we remove financial frictions (column 3). Comparing both columns, we find that overall emissions would increase by 31% or 27 log points (lp) when financial frictions are completely removed. Table 5 looks at the channels driving this result. We find that reductions in emissions per unit of energy lead to a decrease in aggregate emissions of 2 lp, reflecting adoption of better vintages by firms. By contrast, changes in energy over output lead to an increase in aggregate emissions by 3 lp due to the increase in capital intensity allowed by the relaxation of the leverage constraint and the complementarity between capital and energy. The largest effect is however the expansion of GDP, which leads to a 24 lp increase in emissions. The net effect is a significant increase in aggregate emissions of 26 lp.

Table 4: Counterfactuals: steady-states comparison

	(1)	(2)	(3)	(4)
	With financial frictions		No financial frictions	
	$\tau = 30$	$\tau = 100$	$\tau = 30$	$\tau = 100$
Welfare	-.45	-.55	-.29	-.32
Output (Y)	4.31	3.73	5.48	4.90
Emissions (E)	.58	.18	.76	.23
Energy (N)	9.56	3.43	12.67	4.54
Labor (L)	1.00	.96	1.06	1.03
Capital (K)	3.34	1.19	4.43	1.59
TFP	3.66	3.72	4.30	4.50
Var ($\log y$)	2.56	2.51	2.97	2.97
Var ($\log a$)	1.83	1.82	0	0
Var ($\log e$)	2.54	2.53	2.97	2.97
Mass of new firms (p)	.81	.72	2.58	2.30

Notes: Welfare is the household utility evaluated at the steady-state equilibrium, abstracting from the damages implied by emissions. Values N and E are multiplied by 100. TFP is defined as $Y/(K^{\kappa}L^{\lambda})$. "With Financial Frictions" refers to the baseline calibrated model's equilibrium and "No Financial Frictions" refers to the counterfactual steady-state equilibrium with $\chi \to +\infty$.

These quantitative results show that while relaxing financial constraints does improve environmental performance through adoption of greener technology, it also increases output and capital intensity, which results in higher aggregate emissions. The increase in output happens through productivity improvements and firm entry. In other words, financial frictions are barriers to green technology adoption, but lifting them wouldn't necessarily help with emission reductions.

The increase in output generated by the removal of financial constraints in our model is consistent with earlier work looking at the costs of misallocation. For example, Buera et al. (2011) find that the misallocation costs of financial frictions can be up to 40% of aggregate TFP in developing economies. However, the quantitative impact of misallocation remains debated. Midrigan and Xu (2014) argue that the TFP losses from misallocation are around 5-10% in a model calibrated to Korea. Ottonello and Winberry (2024) find similar magnitudes for the U.S..

Table 5: Decomposing the effect on emissions relative to initial steady-state with financial frictions

	$\frac{e}{n}$	$\frac{n}{y}$	Total
Financial frictions			
$\tau = 100$	-.12	-1.00	-1.16
No frictions			
$\tau = 30$	-.02	.03	.26
$\tau = 100$	-.16	-1.03	-.90

Notes: This table decomposes the total log changes in aggregate emissions in the three counterfactual equilibria relative to the baseline equilibrium. The first and second columns measure the contribution of changing emission over energy and energy over output, respectively. All values are in log points.

8.2 Costs and Effectiveness of Carbon Pricing

We now analyze the implications of an increase in the carbon price. We do so first in our calibrated model with financial frictions and then in an alternative setting in which we remove them, as in the first counterfactual. The goal is to understand how financial frictions shape the cost and the effectiveness of carbon pricing, as well as the channels through which it affects the equilibrium allocation.

With Financial Frictions. This counterfactual simulates a realistic increase in the price of carbon in Europe from €30 to €100. The calibration of the future price of carbon is consistent with publicly available forecasts.[26] We keep the level of financial constraints χ unchanged.

An increase in the price of carbon from €30 to €100 is predicted to decrease emissions by 68.5% but also to decrease GDP by 13%. This amounts to 1.8% of GDP loss for each €10 increase in the carbon price. This magnitude is consistent with other estimates of the long-run costs of carbon prices derived in calibrated models. For example, (Goulder and Hafstead, 2017) find a cost of about 1 percent of GDP. It is higher than the empirical estimates by Metcalf and Stock (2020) and the recent model-based estimates by Finkelstein Shapiro and Metcalf (2023) and Capelle et al. (2024). This body of prior work focuses on real investment frictions, while we focus on financial constraints. This

[26] Forecasts can be found here.

highlights that while real investment frictions can rationalize a very small negative impact of carbon prices on GDP, financial frictions cannot.

In the presence of financial frictions, a rise in the cost of carbon impacts aggregate output through traditional as well as new channels. The increase in the cost of emissions leads firms to change their optimal input mix, consume less energy, and invest less in capital, which is complementary with energy. It also incentivizes firms to adopt greener vintages. These are the traditional substitution effects. Additionally, with financial frictions, the increase in the cost of energy slows down firm growth, due to lower profits. As a result, the average firm size decreases. Relatedly, in general equilibrium, fewer firms find it profitable to enter and the overall mass of firms decreases. In addition, wages fall, which lowers labor supply. Overall, aggregate capital declines by 64% and aggregate labor decreases by 3.5%. Finally, the rise of the carbon tax increases aggregate TFP by 1.6% due to an improvement in the allocation of capital across firms as in Kim (2025). We however find much smaller effects than in this paper. Unreported figures show that the variance of marginal products of capital decreases.

Transition. The different channels through which an increase in carbon prices affects the equilibrium allocation unfold at dissimilar paces. Two of these channels—the lower entry of firms and the slower accumulation of net worth—unfold slowly while the others—change in input mix and adoption of greener vintages—happen quickly after the increase in carbon prices. To analyze the contribution of different channels and the pace at which they unfold, we now trace out the transition of the economy from the baseline steady state following a one-time and permanent increase in the price of carbon from $€\tau = 30$ to $€\tau = 100$. Results are displayed in Appendix Figure A15.

In the simulation of the transition path, we find that the short-run decline in GDP is about 7%. Over the following decades, GDP continues to decline slowly as incumbent firms die and younger firms find it more difficult to grow. After several decades, the cumulative long-run decline amounts to a total of 13% of the initial level of GDP. Emissions follow a different path: most of the reduction happens in the very short run. On impact emissions decline by 66%. The slow adjustment leads to an additional reduction, bringing the total fall to 68.5%.

Without Financial Frictions. To further understand how financial frictions shape the effectiveness of carbon prices in terms of emissions reduction and output costs, we run

a third counterfactual in which we increase the carbon price τ from €30 to €100 and we lift financial frictions $\chi \to +\infty$. The steady state resulting from both policy changes is reported in the fourth column of Table 4.

Compared to the baseline steady state with financial frictions and a moderate carbon price of €30 (first column) we find that the decrease in emissions implied by the increase in the price of carbon is partially offset by the lifting of financial frictions. Quantitatively, emissions decrease by 60%, consistent with the first counterfactual that showed that removing financial frictions results in higher emissions despite the wider adoption of greener vintages. Similarly, the decrease in GDP implied by carbon prices is more than offset by the removal of frictions and aggregate output ends up increasing by 13.7%.

However, if we look at the impact of carbon pricing holding the degree of financial frictions fixed—i.e. comparing line 2 to 1, and line 4 to 3—we see that carbon pricing is more effective in the absence of financial frictions. Quantitatively, the decrease in emissions amounts to $.76 - .23 = -.53$ without financial frictions which is larger than the decrease of $.58 - .18 = -.40$ with financial frictions. Output decreases by .58 in both cases. This suggests that the effectiveness of carbon pricing for mitigating emissions is reduced by financial frictions.

Intuitively, these effects are driven by the fact that unconstrained firms react more strongly to the carbon price. There are several channels driving this result. Given the initial distribution of net worth, unconstrained firms are more likely to adopt better vintages. In addition, the increase in emission costs also weighs more heavily on constrained firms which accumulate net worth less quickly, thus slowing down their growth and their adoption of better technologies.

8.3 Green Financial Policies

Limits to the implementation of first-best policies. When there are no costs to implementing policies, the first-best allocation requires financial sector policies addressing financial frictions and a carbon price aligning private abatement costs with the social cost of carbon, in the spirit of our third counterfactual in Section 8.1. When there is no obstacle to the implementation of these financial policies and carbon pricing, there is a complete separation of objectives and there is no need for financial policies to be green.

However, both financial policies and carbon pricing have implementation costs limiting their deployment. Financial sector policies result in moral hazard and fiscal costs

which may entail distortionary taxation, and carbon pricing faces political economy constraints. As a result, incorporating such constraints results in a different first-best policy mix. In this context, there may be scope for green financial policies to complement carbon pricing and for carbon pricing to take into account distortions implied by financial frictions (Döttling and Rola-Janicka, 2022; Heider and Inderst, 2022).

Green Financial Policies in Europe. In Europe, a number of green financial policies aim at giving incentives to firms to green their production processes, through public loans, guarantees and interest rate subsidies. In this section, we look at the welfare implications of different mixes of green financial sector policies and carbon prices. Our goal is to understand whether there is scope for green financial policies, i.e. policies that are targeted to firms borrowing to invest in greener technologies.[27]

To do so, we incorporate in the model one specific green financial policy that is considered in practice in Europe: public lending and debt guarantees to firms based on the degree of greenness of the capital stock. More specifically, we assume that the leverage constraint $\chi(.)$ is a simple function of the firm's vintage:

$$\chi(v) = \chi + \omega_\chi \times \mathbb{1}(v \geq \underline{\omega}_\chi) \tag{45}$$

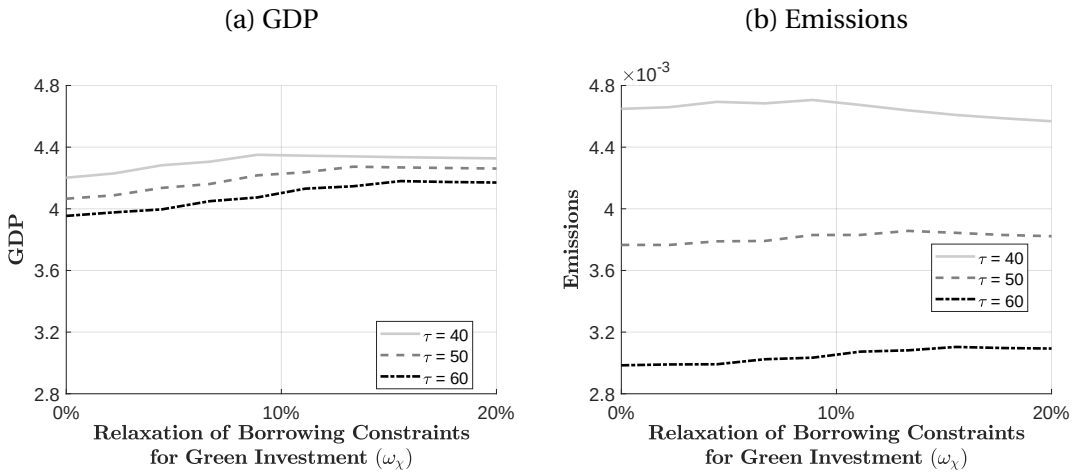
where ω_χ governs the generosity of the policy, i.e. the degree to which it relaxes the borrowing constraint faced by firms, and where $\underline{\omega}_\chi$ governs the degree of green bias. We say that the policy is green biased if and only if $\underline{\omega}_\chi > 0$.

Results. Figure 8 traces out the equilibrium GDP and aggregate emissions for different degrees of generosity of the green credit policy ω_χ, holding the level of carbon prices τ fixed. The x-axis corresponds to the degree of relaxation of the financial constraint, in percentages of the baseline level of $\chi = 2.2$. The three different lines correspond to three levels of carbon prices. The degree of green bias $\underline{\omega}_\chi$ of the policy is held fixed at $\underline{\omega}_\chi = 1.1$, which is the value of the best vintage used by unconstrained firms in equilibrium (see Figure 7).

The main result is that green financial policies, holding carbon prices fixed, do not offer an easy way to reduce emissions. While they provide strong incentives for firms to

[27] Solving for the second-best optimal mix of policies is beyond the scope of the paper, which would require a detailed modeling of the costs of financial policies and carbon pricing. Instead, we simply compare the properties of different mixes of policies.

Figure 8: Impact of relaxing the borrowing constraint (ω_χ)



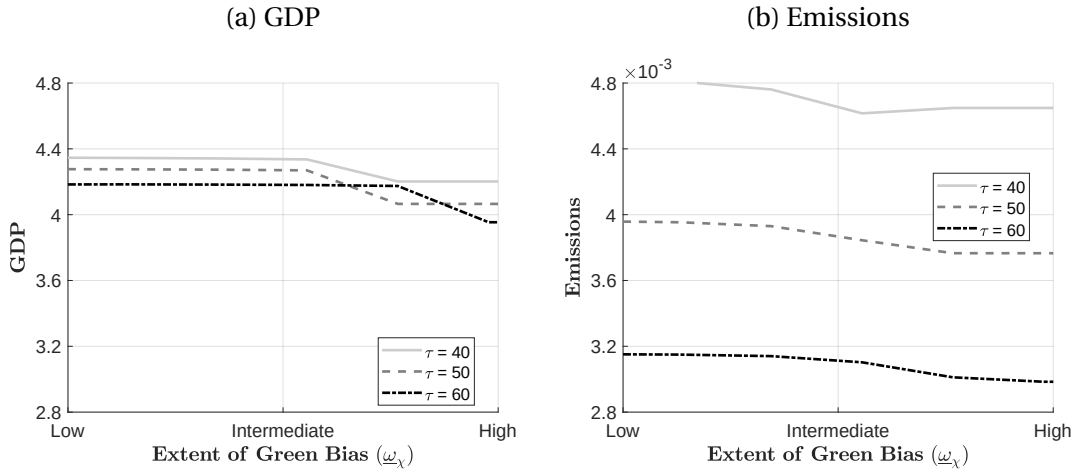
Notes: This graph shows the impact of relaxing the borrowing constraint parameter χ by up to 20%, which corresponds to an increase in the parameter ω_χ, on GDP (left panel) and emissions (right panel). Each line corresponds to a different level of the carbon tax.

adopt greener vintages they also boost aggregate output in general equilibrium, albeit to a smaller extent than financial policies without a green bias. Quantitatively, Figure 8 shows that relaxing the borrowing constraint by 10% only for greener investments leads to an increase in GDP by 3.7% and in aggregate emissions by 1.8%, despite a wider adoption of greener vintages. Even when they are green biased, financial policies are still not an effective policy to cut emissions. They are however an appealing instrument if the goal is to boost GDP while minimizing the rise in emissions.

We also find that further restricting the set of vintages eligible to public loans and guarantees could cut emissions but with a cost in terms of GDP. Restricting financial policies to the greenest vintage is an interesting exercise, as the ECB is deciding whether to bias its portfolios of assets towards greener bonds. We thus perform another simulation in which we vary the degree of green bias $\underline{\omega}_\chi$ holding the increase in generosity fixed at 15%. Results are shown in Figure 9, where the x-axis corresponds to the extent of green bias of financial policies. On the left side of the x-axis, the extent of bias is "low", and all vintages are eligible to public loans and guarantees; in the middle of the axis the bias is "intermediate" and the policy applies to vintages only above $\nu = 1$; and on the right side of the x-axis the bias is "high" and the policy is restricted to the greenest vintage. Quantitatively, we find that increasing the extent of green bias from "intermediate"

to "high" leads to a decrease in aggregate emissions by 3.2%, through wider adoption of greener vintages, but at the cost of a decrease in GDP by 3.5%. Overall, greening existing financial policies, holding carbon prices fixed, does not offer an easy way to reduce emissions.

Figure 9: Impact of increasing the green bias of financial policies ($\underline{\omega}_\chi$).



Notes: This graph shows the impact of increasing the green bias of financial policies ($\underline{\omega}_\chi$) on GDP (left panel) and emissions (right panel). Different shades of gray correspond to different levels of the carbon tax. "Low" corresponds to a policy that covers all vintages while "High" corresponds to one that covers only the greenest vintage.

9 Conclusion

Many jurisdictions have introduced or are considering green financial sector policies. However, the literature offers little evidence on how financial frictions and policies to alleviate them matter for total emissions—and how they interact with carbon pricing.

This paper offers new theoretical and empirical evidence. Importantly, less financially constrained firms are better able to respond to carbon pricing. Relative to peers within narrow industries, less constrained firms are able to respond to exogenous increases in carbon prices by cutting emissions, at little apparent cost to the scale of their operations—suggesting that these firms make investments that help improve environmental efficiency. Importantly, these results are driven by firms far from the current productivity frontier within their industry.

We propose a tractable heterogeneous-firm general equilibrium model of investment across different capital vintages subject to financial constraints to rationalize these findings. Firms in the model face a key tradeoff: they can invest in more efficient capital vintages, but this may reduce their ability to scale their capital stock up towards optimal size. The model both qualitatively and quantitatively matches our empirical evidence.

Counterfactual simulations from a calibrated version of the model show that, in general equilibrium, policies that aim to relax financial constraints—including policies with green bias—end up raising total emissions because they allow GDP to grow. Holding carbon taxes fixed, while strengthening the extent of green bias in these policies can help cut emissions, this comes at significant cost to GDP.

Our modeling approach also reveals new channels through which higher carbon taxes have economic costs. In the presence of financial frictions, carbon taxes that raise the cost of emissions slow growth for young, constrained firms. A reduction in expected profits also reduces entry rates. These costs take time to materialize and are quantitatively important. Financial frictions are therefore an important element of the macroeconomics of climate change.

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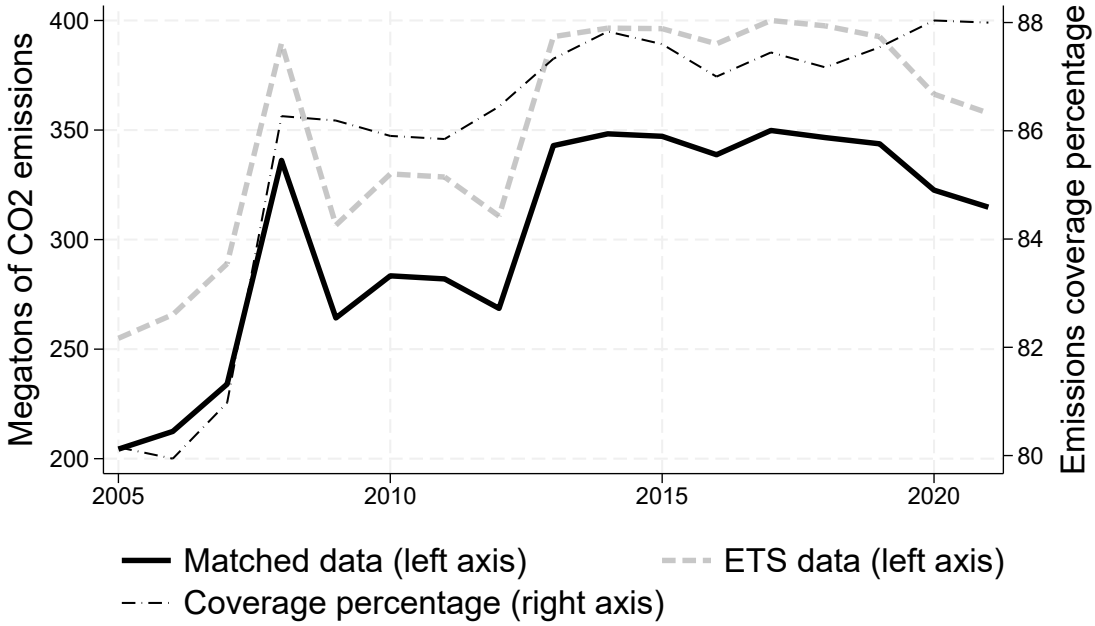
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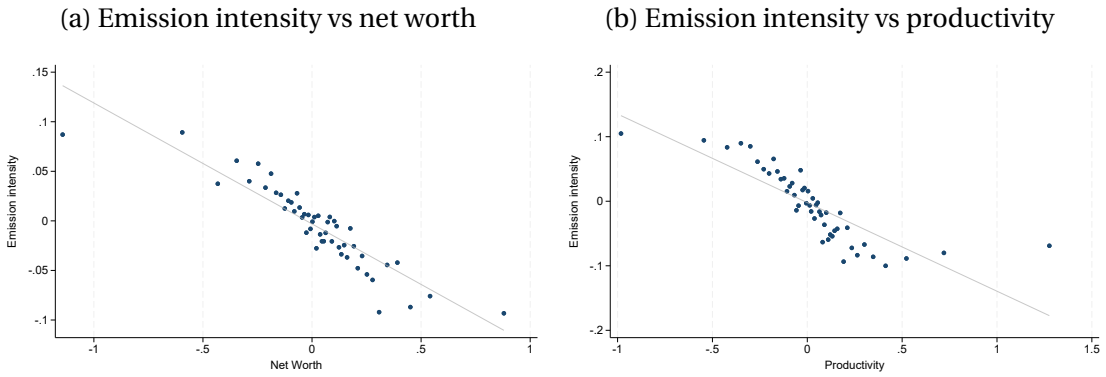
A1 Annex: Figures and Tables

Figure A1: Sample coverage of ETS manufacturing emissions



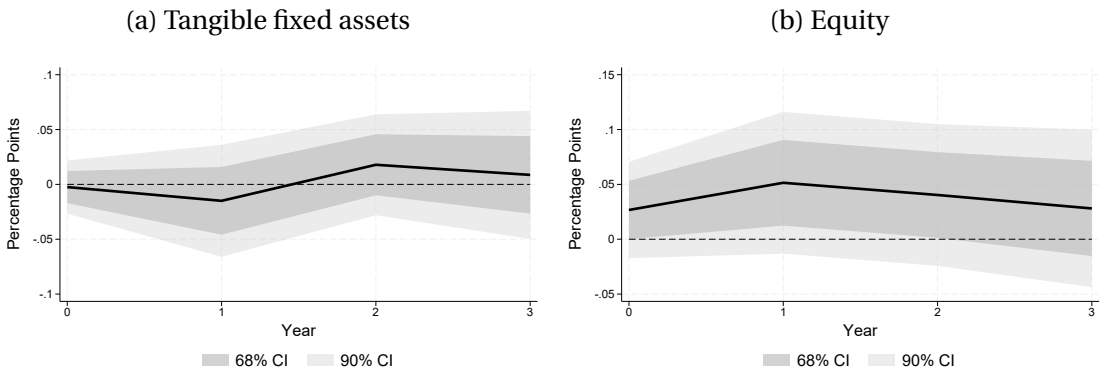
Notes: This figure shows the evolution of the aggregate manufacturing emissions covered by the EU-ETS (ETS data) and those of our final sample (matched data), as well as the percentage that the latter represent of the former (coverage percentage).

Figure A2: Less financially constrained and more productive firms have lower emission intensities



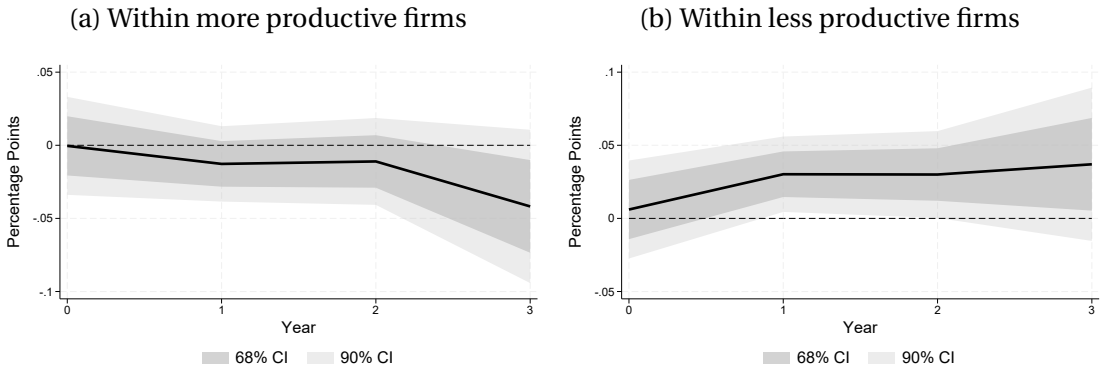
Notes: The figure displays binned scatter plots of emission intensities (the logarithm of emissions over value added) against the net worth (panel a) and the productivity (panel b) of the firm. All variables are residualized against firm + year fixed effects and standardized. Only manufacturing firms are included.

Figure A3: Cumulative differential responses to carbon price shocks for less financially constrained firms



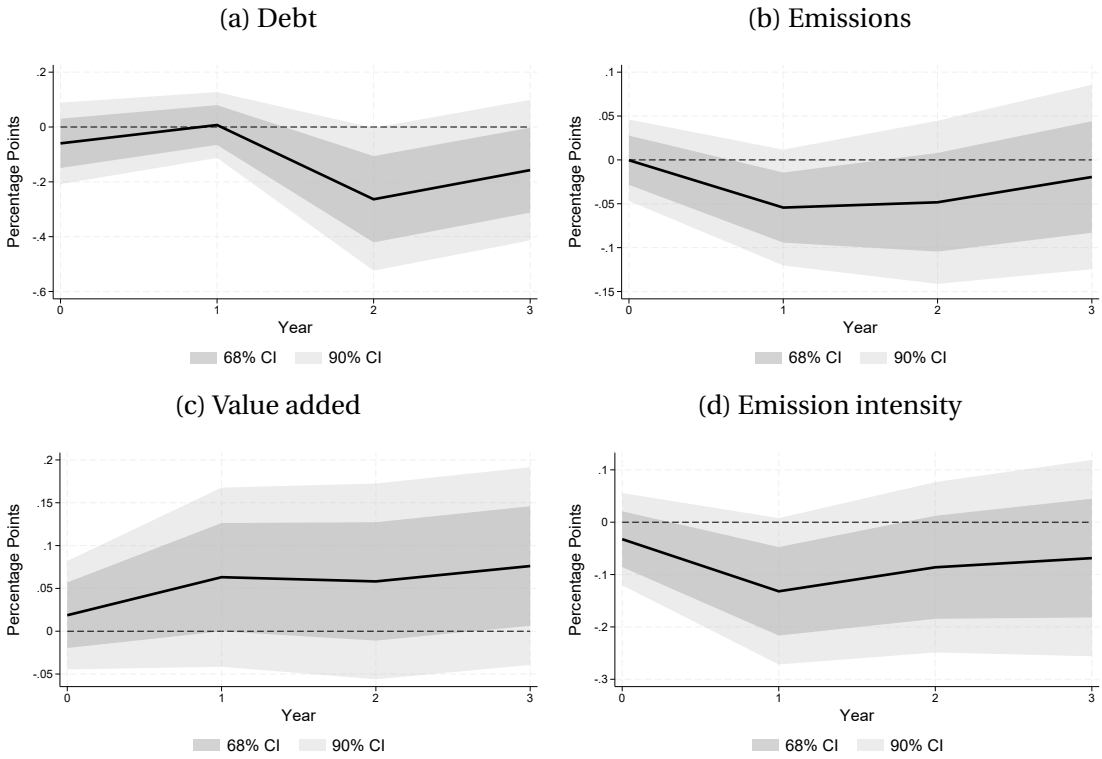
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A4: Cumulative differential productivity response to carbon price shocks for less financially constrained firms



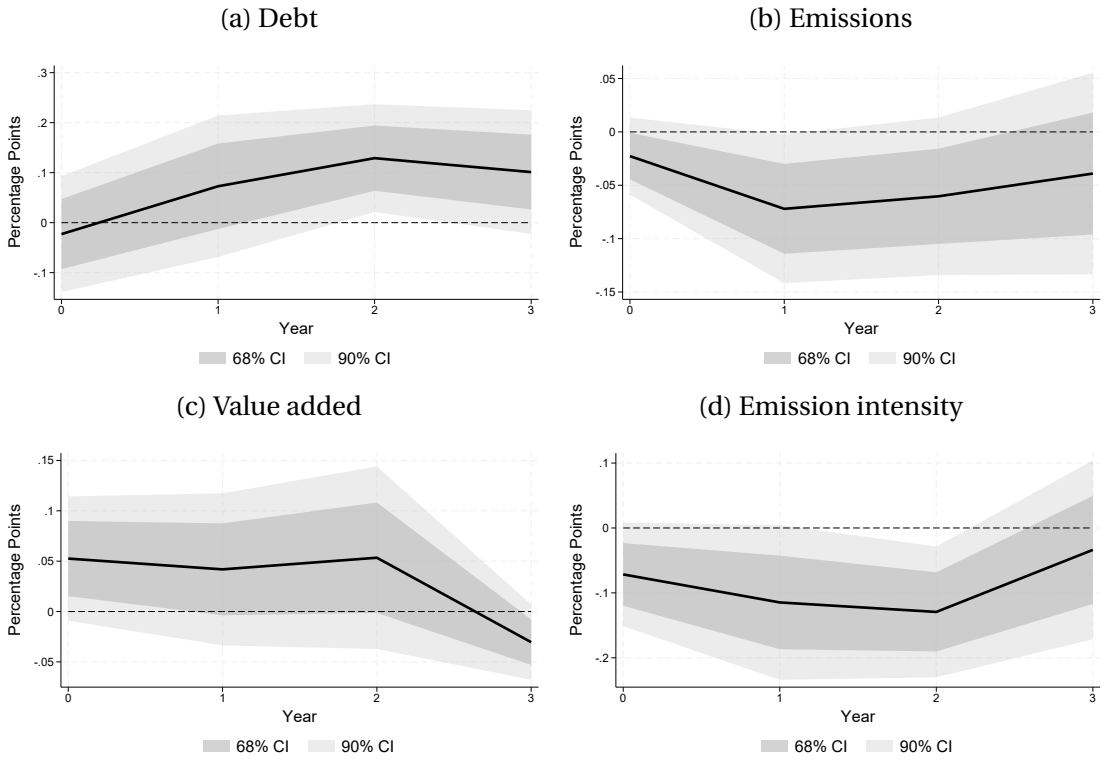
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, separately for high and low productivity firms, estimated using Equation (2). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. A firm is classified as having high productivity if its productivity exceeds the median of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A5: Cumulative differential impulse responses to carbon price shocks by firms facing low levels of financial constraints, defining financial constraints using leverage



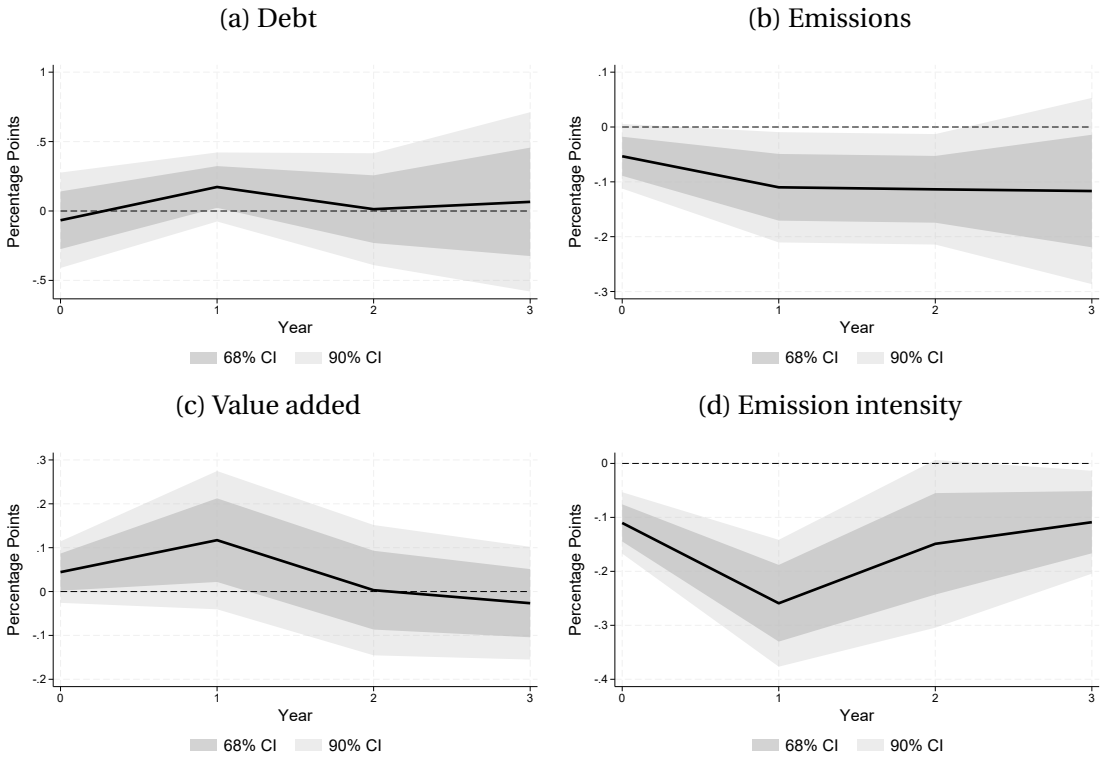
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its leverage is below the 25th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A6: Cumulative differential impulse responses to carbon price shocks by firms facing low levels of financial constraints, defining financial constraints using size (total assets)



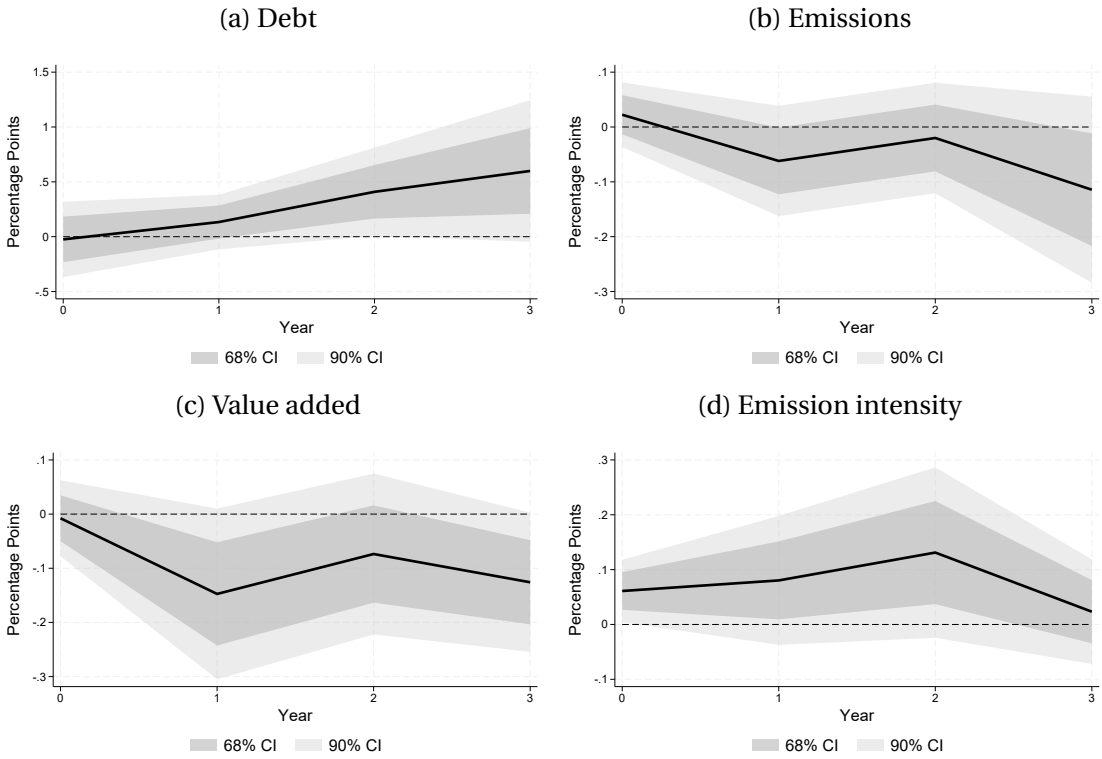
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its total assets are above the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A7: Cumulative differential responses to carbon price shocks for less financially constrained firms, within firms with older capital stock



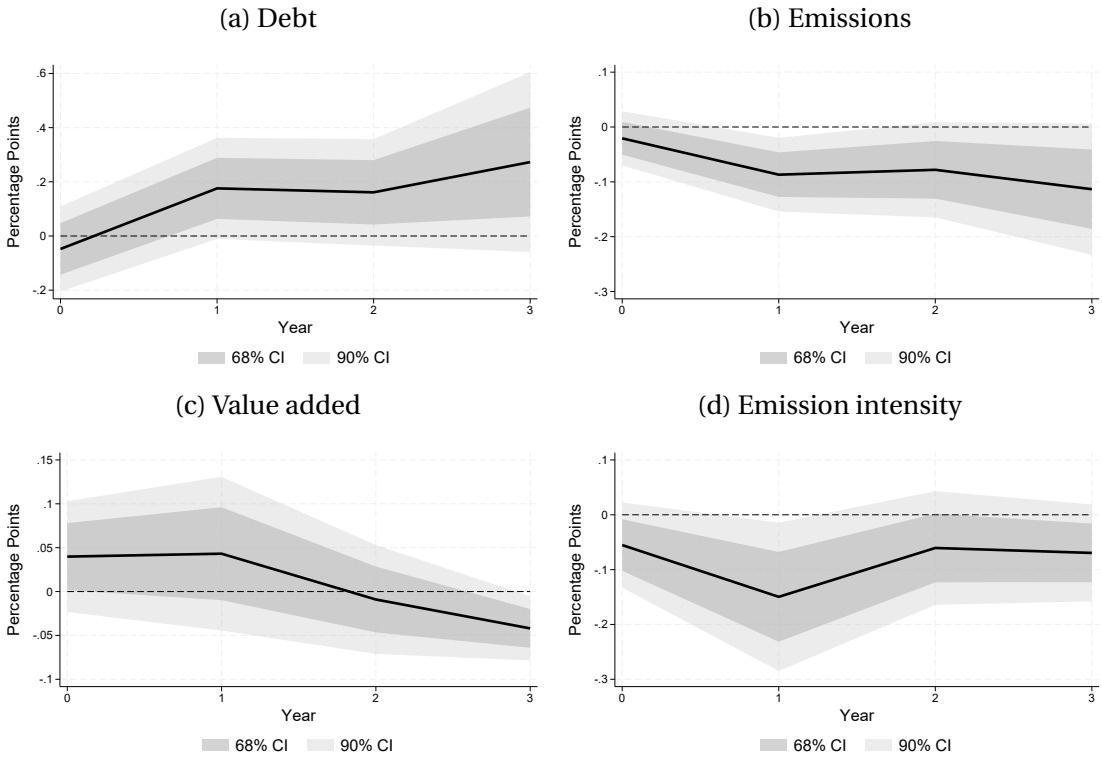
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, separately for firms with newer and older capital stock, estimated using Equation (2). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. A firm is classified as having old capital stock if the average age of its capital exceeds the median of the distribution within its industry and country. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A8: Cumulative differential responses to carbon price shocks for less financially constrained firms, within firms with newer capital stock



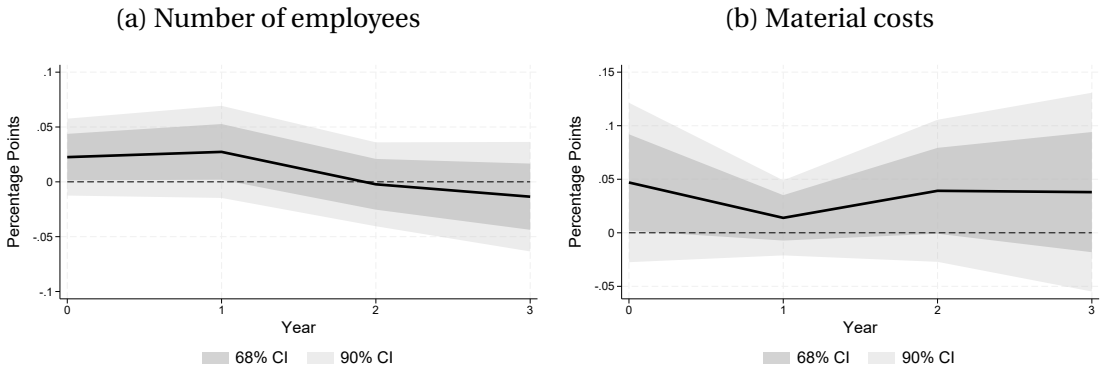
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, separately for firms with newer and older capital stock, estimated using Equation (2). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. A firm is classified as having old capital stock if the average age of its capital exceeds the median of the distribution within its industry and country. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A9: Cumulative differential responses to carbon price shocks for less financially constrained firms, controlling for total assets



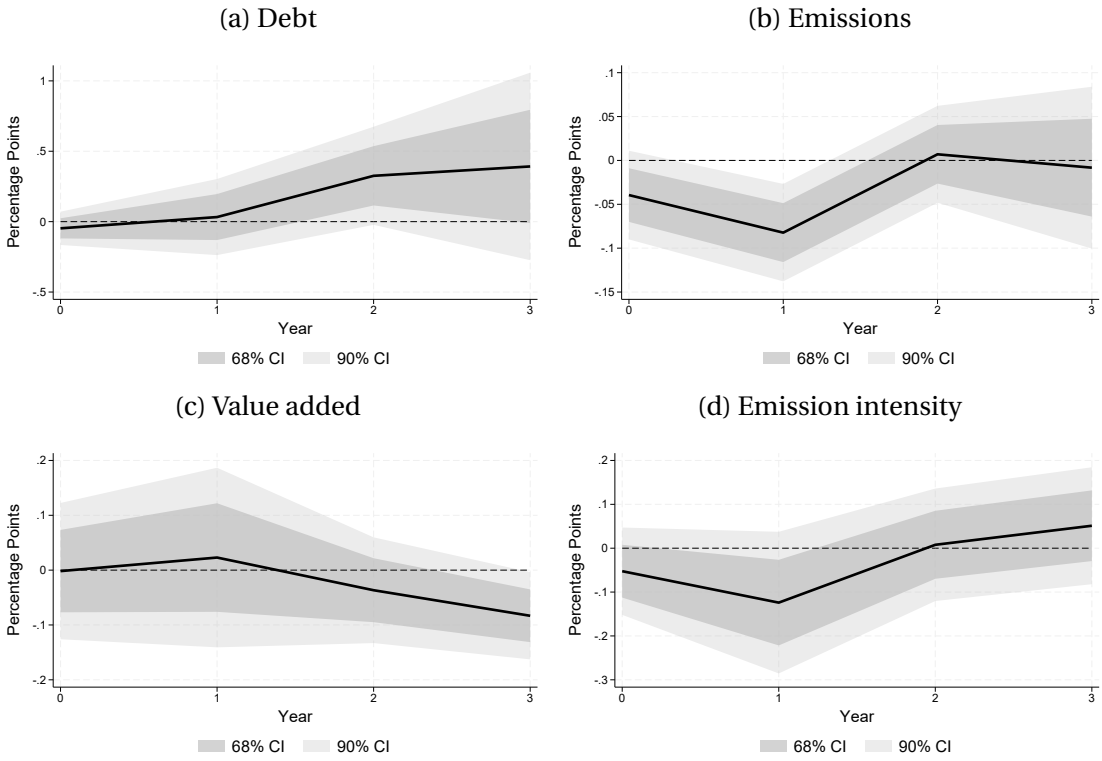
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A10: Cumulative differential responses to carbon price shocks for less financially constrained firms



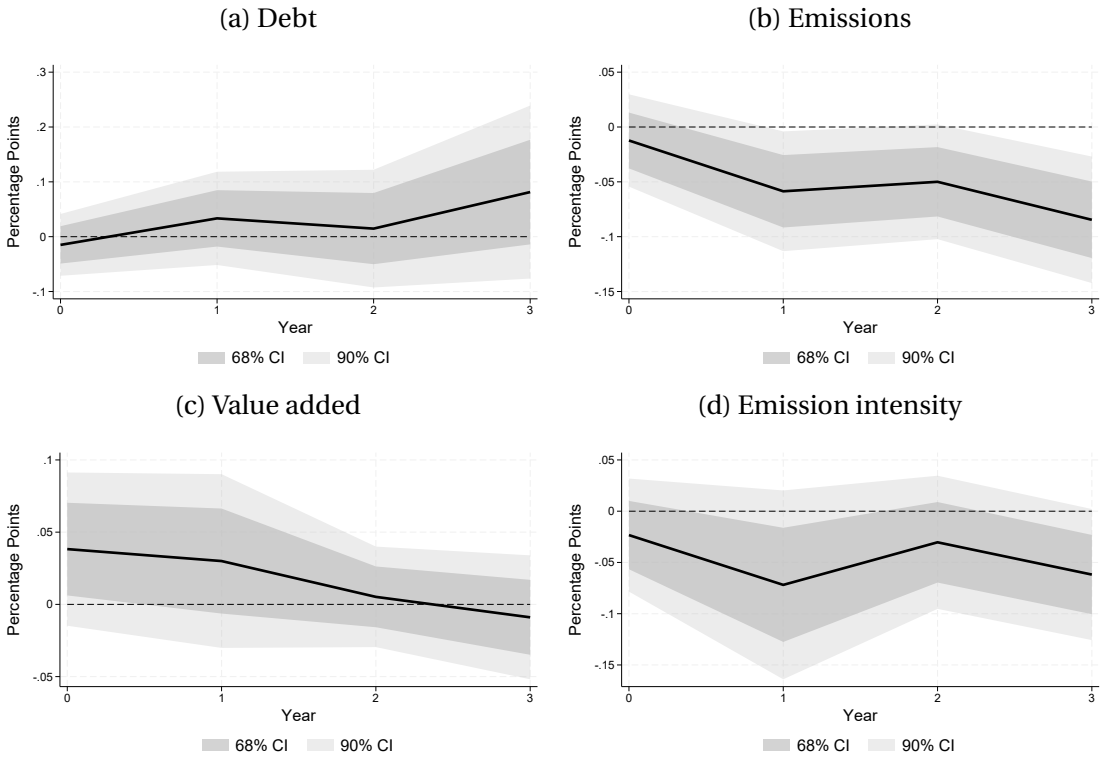
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A11: Cumulative differential responses to carbon price shocks for less financially constrained firms, for firms for which the number of recorded installations in Orbis does not exceed the number recorded under the EU ETS



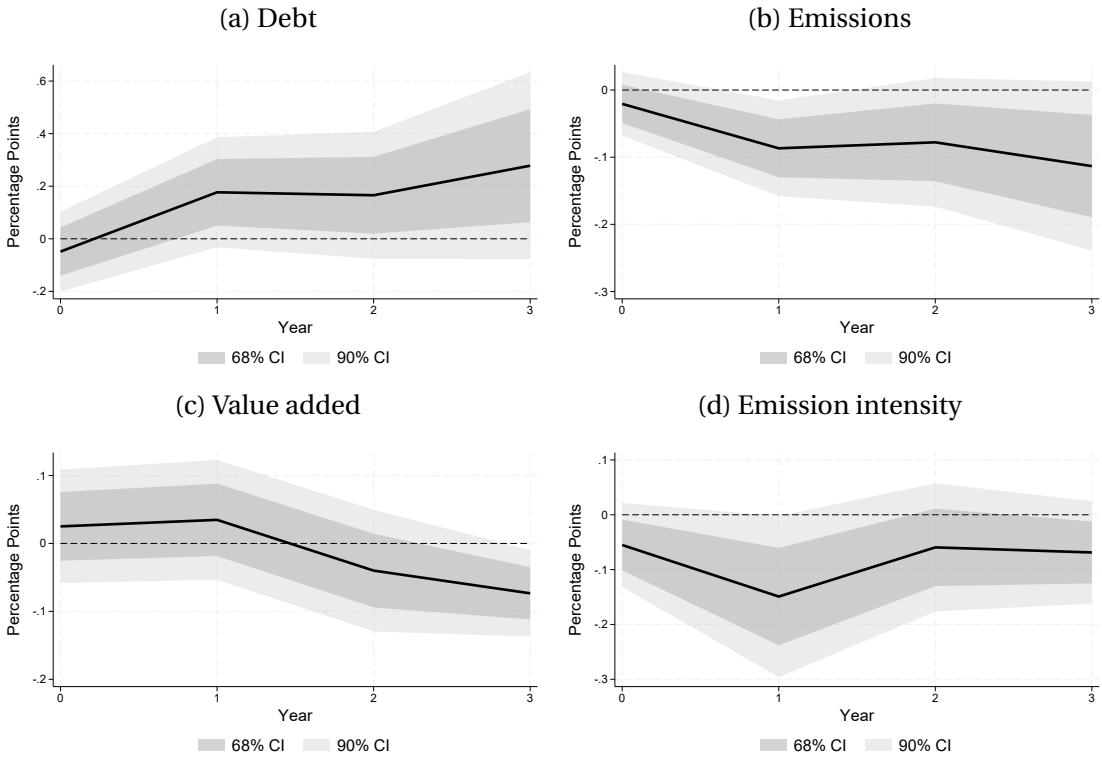
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms for which the number of recorded installations in Orbis does not exceed the number recorded under the EU ETS. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A12: Cumulative differential responses to carbon price shocks for less financially constrained firms, using firm and time fixed effects



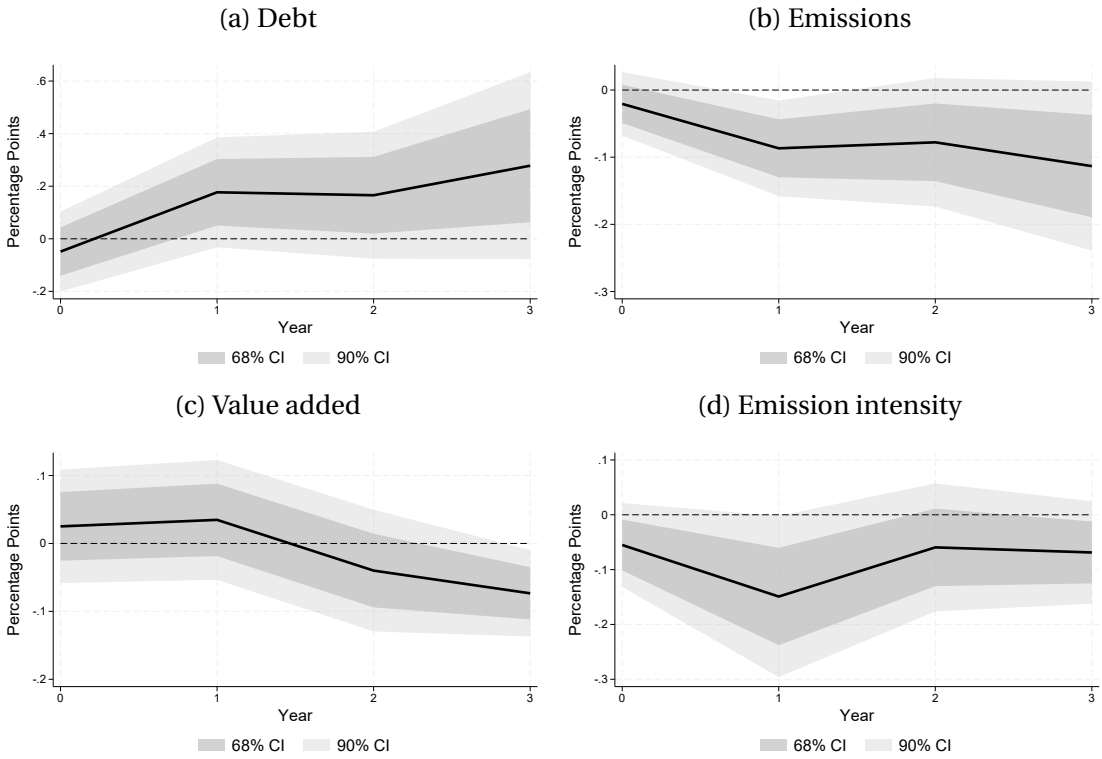
Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the year level.

Figure A13: Cumulative differential responses to carbon price shocks for less financially constrained firms, clustering at the firm and year level



Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Standard errors are clustered at the firm and year level.

Figure A14: Cumulative differential responses to carbon price shocks for less financially constrained firms, using robust standard errors



Notes: This figure shows cumulative differential impulse responses for firms facing low levels of financial constraints to carbon price shocks, relative to firms facing high levels of financial constraints, estimated using Equation (1). A firm is classified as facing low levels of financial constraints if its net worth exceeds the 75th percentile of the distribution within its industry, country, and year. Only manufacturing firms are included. Impulse responses are shown over a 3-year horizon, with confidence intervals (CIs) at 68% and 90% levels. Robust standard errors.

A2 Model - Appendix

A2.1 Additional derivations

To derive the optimal choice of capital and labor, we write down the Lagrangian associated with the profit maximization problem (17) for a given vintage, v. Denoting Λ the Lagrange multiplier associated with the financial constraint (19), the FOCs are given by

$$(\ell) \quad \lambda \frac{y}{\ell} = w_t \tag{46}$$

$$(k_v) \quad \kappa \frac{y}{k} = r_{vt}\left(1 + \Lambda\left(r^* + \delta - \frac{\dot{q}_{vt}}{q_{vt}}\right)^{-1}\right) + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v} \tag{47}$$

There are two cases. Either the firm is constrained, or it is not. If the firm is unconstrained then we can substitute in the production function:

$$y = z\left(v\frac{\kappa y}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v}}\right)^{\kappa}\left(\frac{\lambda y}{w_t}\right)^{\lambda} \tag{48}$$

This pins down an optimal size as long as $\kappa + \lambda < 1$

$$y = \left(z\left(v\frac{\kappa}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v}}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right)^{\frac{1}{1-\kappa-\lambda}} \tag{49}$$

And profits are given by

$$\pi_t(v,z) = \left(z\left(v\frac{\kappa}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v}}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right)^{\frac{1}{1-\kappa-\lambda}}[1-\lambda-\kappa] \tag{50}$$

The optimal level of capital in the unconstrained case is given by

$$k_v = \left(\frac{\kappa}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v}} \right)^{\frac{1-\lambda}{1-\lambda-\kappa}} p^{\frac{1}{1-\kappa-\lambda}} \left(z v^{\kappa} \left(\frac{\lambda}{w_t} \right)^{\lambda} \right)^{\frac{1}{1-\kappa-\lambda}} \tag{51}$$

$$= \frac{\kappa}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v}} \left(z \left(v \frac{\kappa}{r_{vt} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v}} \right)^{\kappa} \left(\frac{\lambda}{w_t} \right)^{\lambda} \right)^{\frac{1}{1-\kappa-\lambda}} \tag{52}$$

In the case where the firm is constrained, we have $k_v = \frac{\chi a_t}{q_{vt}}$ and output and labor are given by

$$y = z \left(v \frac{\chi a_t}{q_{vt}} \right)^{\kappa} \left(\frac{\lambda y}{w_t} \right)^{\lambda} \iff y = \left[z \left(v \frac{\chi a_t}{q_{vt}} \right)^{\kappa} \left(\frac{\lambda}{w_t} \right)^{\lambda} \right]^{\frac{1}{1-\lambda}} \tag{53}$$

$$\ell = \left[z \left(v \frac{\chi a_t}{q_{vt}} \right)^{\kappa} \left(\frac{\lambda}{w_t} \right) \right]^{\frac{1}{1-\lambda}} \tag{54}$$

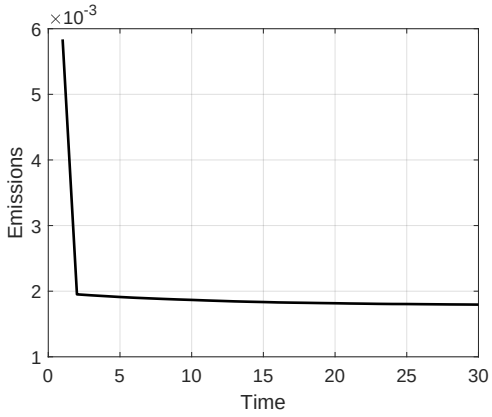
And profits are given by

$$\pi_t(v,z) = \left[z \left(v \frac{\chi a_t}{q_{vt}} \right)^{\kappa} \left(\frac{\lambda}{w_t} \right)^{\lambda} \right]^{\frac{1}{1-\lambda}} [1-\lambda] - \chi a_t \left(r^* + \delta - \frac{\dot{q}_{vt}}{q_{vt}} + \frac{m_t + \tau_t v^{-\gamma}}{\eta_v q_{vt}} \right) \tag{55}$$

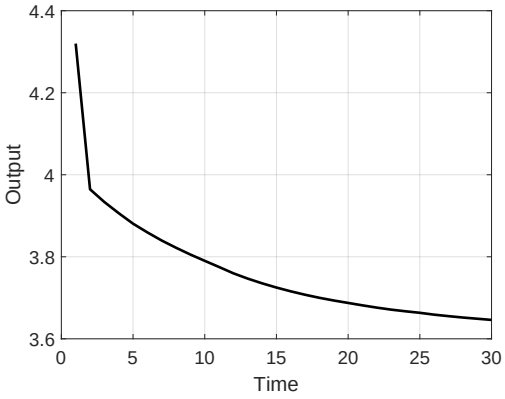
A2.2 Transition

Figure A15: Transition after an increase in carbon price from €30 to €100

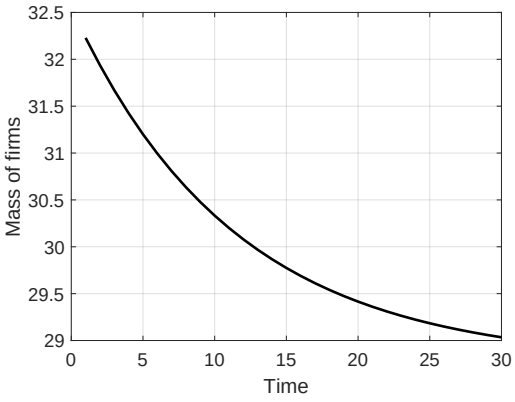
(a) Emissions



(b) Output



(c) Mass of firms



(d) Average firm's net worth

