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Mitigating Climate Change at the Firm Level: Mind the Laggards
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ABSTRACT: We document significant within-industry heterogeneity in environmental performance across firms globally and across sectors. We find that this heterogeneity is in part driven by newer capital-embedded technologies and intangible investments that raise productivity. We propose a multi-sector heterogeneous-firm general equilibrium model which endogenizes these novel determinants and matches the extent and drivers of firm heterogeneity. Calibrated simulations for several countries reveal the importance of adoption of newer capital-embedded technologies in lowering the costs of mitigation policies. We highlight the trade-off between short-term costs and long-term benefits of subsidies for capital upgrading.

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1 Introduction

Carbon taxes and subsidies are important tools for policymakers to reduce corporate emissions and combat climate change (Blanchard et al., 2023; Kammer, 2023; Draghi, 2024). Strikingly, many firms lag well behind the current frontier of environmental performance—at least in US manufacturing (Lyubich et al., 2018). Whether emission cuts at laggard firms represent low-hanging fruit that mitigation policies should leverage depends critically on the factors driving heterogeneity across firms and how firms respond to policies. To enhance policy design, more evidence is needed on the factors driving firm-level heterogeneity in environmental performance.

In this paper we make five contributions to fill these gaps. First, we document significant within-industry heterogeneity in environmental performance across firms globally and across sectors. Second, we show that such heterogeneity is in part driven by two novel factors: newer capital-embedded technologies and intangible investments that raise productivity. Third, we propose a multi-sector heterogeneous-firm general equilibrium model which endogenizes these determinants and matches the heterogeneity in firm environmental performance. Fourth, we calibrate the model for several countries. Fifth, we use the calibrated model to investigate the implications of the extent and drivers of firm heterogeneity for climate mitigation policies.

We begin by documenting that many large listed firms lag significantly behind the current environmental performance frontier across countries and sectors. Drawing on self-reported data on greenhouse gas emissions for a global sample of more than 3,000 listed firms, we show that firms differ widely in their emission intensities—emissions per dollar of revenues—within the same industries and countries.[1] Emission intensities for firms at the 90th percentile of the within-country and industry distribution are six times larger than for firms at the 10th percentile. This is comparable to dispersion in labor productivity, and much larger than in total factor productivity (Syverson, 2011).

We show that two technological factors play an important role in explaining such heterogeneity: technologies embedded in newer vintages of physical capital, and intangible investments in improving productivity. More specifically, climate laggards use older physical capital and have a lower share of intangible capital. Additionally, climate laggards are less effective on other dimensions as well: they display lower labor

[1]We focus on a sample of firms in manufacturing, transportation, and services for which Scope 1 and 2 emissions were 5.8 Gigatons of Carbon (GtC) in 2020, or about 16 percent of global emissions.

productivity, are less profitable, and use worse management practices.

Importantly, we find that capital embedded technologies are green-biased: they reduce emissions even beyond lowering energy consumption. Put differently, newer capital-embedded technologies appear to facilitate using greener sources of energy. In contrast, improvements in productivity due to intangible investments only reduce energy consumption per unit of revenue. Wider adoption of newer and greener vintages of capital may therefore be a powerful lever of emissions reduction.

Instrumental variable approaches and a battery of robustness tests validate our empirical findings. Instrumental variable approaches, based on tax credits across US states (Lucking, 2019) and the pace of firm growth in recent years, suggest that adoption of newer technologies and higher knowledge intensity have a causal impact on emission intensities. In addition, our results are robust to different industry classifications, including text-based approaches drawing on self-identified competitors (Hoberg and Phillips, 2016), and different levels of industry granularity. Overall, we provide new stylized facts that can help discipline a range of firm-level models that study climate change mitigation.

We propose a multi-sector heterogeneous-firm general equilibrium model consistent with our empirical findings to investigate their implications for mitigation policies. Each industry is populated by firms which differ in their capital vintages, knowledge intensities, and size. Firms can choose to upgrade to newer, more efficient, and green-biased vintages of capital and choose how much tangible capital to accumulate. Importantly, investments in the model are partly firm-specific (Kermani and Ma, 2022) and vintages are difficult to combine. Firms also choose intangible investments to increase their productivity. These endogenous state variables—vintage and size of the physical capital stock and intangible capital—in turn shape firms' size, energy, and labor static choices, and ultimately productivity and emissions. In summary, we embed a Hopenhayn (1992) framework in a multi-sector setting and extend previous research (Shapiro and Walker, 2018; Finkelstein Shapiro and Metcalf, 2023) by introducing new margins of responses to mitigation policies. These include capital vintage upgrades and intangible investments.

We show analytically that this rich framework is consistent with the empirical evidence we present on the role of capital vintages and intangible investments. In the cross section of firms within a given industry and country, firms that rely on older vintages of physical capital and invest less in intangibles have higher emission intensities.

Our framework is also consistent with the finding that environmental and economic performance have common drivers. Like in the data, firms with older vintages of capital and lower intangible investments have lower productivity.

We then calibrate the model for multiple countries to match the empirical distribution of firms, the importance of the new margins of response, and the green bias of capital-embedded technologies. Within each industry and country, the model matches the joint distribution of firm size, intangible capital, and capital vintages. Our calibration strategy also targets and matches the IV estimates of both the elasticity of capital productivity and of emissions to vintage age. The latter captures the degree of green bias of capital-embedded technologies. At the country-industry level, we match input intensities in production and emission intensities. Overall, our calibrated model is quantitatively consistent with the new empirical evidence and the distribution of firms in the data.

Motivated by global interest in subsidies to support investments in green technologies, we use the model to analyze the costs and channels of both carbon pricing and subsidies. Specifically, we consider subsidies for purchases of the newest vintage of physical capital and for investments in intangible capital.[2] We calibrate each policy to generate the same 15% reduction in emissions in steady-state.[3] While this is far from the more ambitious goal of the Paris agreement, it is consistent with a medium-run objective (5 to 10 years) and the fact that we abstract from long-run growth.

Counterfactual simulations show that the economic costs of carbon taxes are an order of magnitude smaller than those implied by subsidies, consistent with the notion that carbon taxes are the first-best mitigation tool. While a carbon tax leads to a -0.3% decrease in the net present value of consumption (NPVC), subsidies for the newest

[2]A subsidy to the newest vintage of capital reflects features widespread in real-world policies. Policies often described as "Industry 4.0" subsidize manufacturers' purchases of capital goods embedding certain advanced technologies (as with state-level policies in Michigan, and national policies in Italy, Portugal, or Malaysia, among many examples). Tax incentives to boost investments often exclude older and second-hand assets, as in the UK. Other policies specifically target energy-saving equipment and practices, renewable energy production, or electrical automotive equipment (e.g., the US DOE's Industrial Assessment Centers or the US Inflation Reduction Act).

[3]Fixing the scale of emission reductions across policies (and scenarios) allows us to compare them through an assessment of economic quantities rather than relying on an estimated social cost of carbon and/or the optimal path of emission reductions, which are beyond the scope of this paper. This approach is closer to actual policy-making as nationally determined contributions to the Paris agreement are expressed in terms of emission reductions and countries often implement specific policies to achieve such goals after the contributions have been set.

capital vintage and for intangible capital both lead to reductions of more than 4%. Relative to subsidies, carbon taxes directly incentivize firms to economize on emissions along all margins, including reducing energy consumption, in the most cost-efficient way. In contrast, subsidies are more narrow in scope and distort the efficient allocation of inputs.

Endogenous decisions by some firms to upgrade to newer and greener capital vintages lead to significant reductions in the macroeconomic cost of policies. To show this, we simulate the impact of a carbon tax that achieves a 15% reduction in emissions but under the assumption that firms must continue using the same vintage of capital they start with, and compare it to the impact of achieving the same reduction in emissions in the baseline model where the capital upgrade margin is available to firms. Without this new margin, the carbon tax would lead to a 0.42% decrease in the NPVC, a 31% larger cost than under the baseline model. Moreover, the carbon tax increase needed to achieve the same emission reduction is much higher in this counterfactual ($36.1 instead of $29.1 per CO2e ton). The importance of the upgrade margin is even more striking for subsidies for the newest vintage of capital. Without this margin, subsidies would lead to a drop in the NPVC by 21.9%, an order of magnitude larger than the decline when firms are allowed to upgrade. This margin is unimportant for subsidies for intangible capital since they do not give incentives to firms to upgrade.

The reduction in the cost and necessary size of carbon taxes when firms are able to upgrade their capital vintage is driven by decisions by firms furthest away from the environmental frontier. Since those firms start with the least emission-efficient vintages, a small share of firms upgrading can significantly reduce aggregate emission intensities. Indeed, although only 2.3% of firms choose to upgrade when allowed to do so, this leads to a 31% difference in the economic cost of the carbon tax. It is therefore important that our calibrated model matches the full distribution of firm-level heterogeneity.

Our counterfactual policy analyses point to an intertemporal tradeoff for subsidies for investments in capital-embedded technologies. Upgrading capital stocks requires large short-run investments, but also improves productivity and reduces emissions, which leads to long-run consumption gains. Importantly, these long-run gains are due to the green bias of newer capital-embedded technologies. In contrast, carbon taxes and subsidies to intangible investments lead to similar consumption costs across all periods. Comparisons of welfare impact across policy instruments therefore depend on the discount rate employed by the social planner to evaluate this intertemporal trade-off. We find that the social discount rate required to make subsidies for the newest vintage as appealing as carbon taxes is around 1.5%, well within the range of discount rates considered in the climate change literature (Stern, 2006; Acemoglu et al., 2012; Campbell and Martin, 2021).

Finally, differences in industry composition and technology mix lead to substantial variation across countries in the required carbon tax and subsidies and in the estimated costs. In a sample of 23 countries, the increase in carbon tax needed to achieve a 15% reduction in emissions ranges from under $10 to $60 per ton. The net present value change (NPVC) costs also vary widely. Countries with more energy-intensive industries find vintage upgrades more attractive, which helps reducing these costs. Additionally, NPVC costs and long-run gains from subsidies also vary based on technological characteristics across countries. Countries that start from older capital stocks face lower transition costs, as fewer firms need to upgrade, to achieve a 15% reduction in emissions, and enjoy larger long-run gains. This highlights the importance of considering country-specific factors in policy evaluation and design.

Literature and contributions. This paper contributes to several strands of literature.

Shapiro and Walker (2018) and Lyubich et al. (2018) highlight significant dispersion in firm-level emissions within narrowly defined industries using data from the US manufacturing census. We contribute by documenting large variation in emissions among firms within the same industry and country across manufacturing, transportation, and services in a diverse set of countries. We also contribute to the growing literature on firm-level determinants of greenness (Haller and Murphy, 2012; Greenstone et al., 2012; Goetz, 2019; De Haas and Popov, 2023; De Haas et al., 2024) by documenting–across a broad range of industries–that productivity-enhancing investments, such as capital upgrades and intangible investments, improve environmental performance.

A key contribution of this paper is to bring a multi-sector heterogeneous-firm perspective to the literature on the macroeconomic implications of climate mitigation policies. While the majority of studies in this literature feature a representative firm in each industry (Metcalf, 1999; Annicchiarico and Di Dio, 2015; Metcalf and Stock, 2020; Campiglio et al., 2022), we document that heterogeneity across firms plays an important role in shaping the aggregate effectiveness of policies. A few recent papers have also integrated firm entry, heterogeneity in firm productivity, and the choice between green and brown technologies within a general equilibrium framework (Finkelstein Shapiro and Metcalf, 2023; Finkelstein Shapiro and Nuguer, 2024). Our work advances this literature by incorporating into the model novel sources of heterogeneity–including the age of the capital stock–as well as a technology for firms' emissions disciplined by new empirical findings. Additionally, we provide a detailed mapping between the model and data, capturing the multiple dimensions of firms' heterogeneity. Interestingly, we find that technology adoption reduces the long-term costs of mitigation policies, which helps rationalize the empirical finding that carbon taxes have modest GDP impacts (Martin et al., 2014; Goulder and Hafstead, 2017; Metcalf and Stock, 2020), while Finkelstein Shapiro and Metcalf (2023) conclude instead that technology adoption by new entrants can completely eliminate these costs.

While previous work largely focuses on carbon taxes, we consider a broader set of mitigation policies, including different types of subsidies. Acemoglu et al. (2016) also study subsidies to green technologies; however, their focus is on the energy production sector, not on firms that use energy. Closer to us is thus the recent literature—mostly focused on the US IRA—estimating the macroeconomic impact of green subsides to firms (Hassler et al., 2020; Bistline et al., 2023; Casey et al., 2023). We contribute by proposing a model centered on firm heterogeneity and quantitatively disciplined by firm-level empirical analysis. We also cover several countries outside the US.

Our work is closely related to the nascent literature studying the impact of mitigation policies on firm productivity. Colmer et al. (2024) find that the EU Emissions Trading System improved productivity by encouraging investments in energy-efficient capital, while Kim (2023) and Klenow et al. (2024) show that carbon pricing can improve the allocative efficiency of the economy. We complement by showing that newer capital matters not only because of energy efficiency but also because of its impact on emissions per unit of energy consumed. Indeed, we find that in general equilibrium emission reductions from improving total factor productivity alone may be small. We also study a wider range of mitigation policies, and document how differences in country characteristics matter for policy design.

Finally, our work highlights how investment frictions (Kermani and Ma, 2022) hinder improvements in environmental performance.[4] Previous studies have examined vintages within specific industries (Barahona et al., 2020; Jacobsen et al., 2023). Our work emphasizes the importance of recognizing laggard firms in understanding the macroe-

[4]See Gillingham and Stock (2018) and Popp et al. (2010) for review papers discussing barriers to mitigating climate change and technology adoption including significant irreversibility of investments.

conomic implications of mitigation policies. While Lanteri and Rampini (2023) focus on maritime shipping and financial frictions, we incorporate heterogeneous vintages into a broader macroeconomic model to assess the effectiveness of diverse mitigation policies.

The remainder of the paper is structured as follows. Section 2 describes the data. Section 3 documents large within-industry and country heterogeneity in emission intensity. Section 4 investigates the drivers of this heterogeneity. Section 5 presents the model, and Section 6 the calibration strategy. Section 7 discusses counterfactual simulations. Section 8 concludes.

2 Data

We combine firm-level data on emissions, balance sheets, and income statements for more than 3,000 listed firms, headquartered in 65 countries, over 2010-2022.[5]

Data on annual emissions at the firm level—self-reported following the Greenhouse Gas Protocol—is from ICE Data Services. We focus on CO2 equivalent scope 1 (direct) and scope 2 (indirect emissions from purchased energy) emissions. Given our interest in within-industry heterogeneity in emissions, it is important that we exclude imputations based on industry averages. We therefore restrict the sample to observations based on firm disclosures.

We gather balance sheet and income statement data from S&P Compustat Global. The data covers corporations that issue publicly traded securities. We use data on energy consumption from DataStream.[6]

As market incentives are at the core of our analysis of climate mitigation policies, we exclude sectors in which firms' investment decisions are often shaped by direct public interventions and ownership rather than market forces. Specifically, we exclude finance, insurance, real state, public administration, utilities, railroad transportation, and local and interurban passenger transit sectors.

We utilize four industry classifications, each with multiple levels of granularity. Three of these, the Standard Industrial Classification (SIC), which we use in our main speci-

[5] 80% of the firms are headquartered in advanced economies (Appendix Figure A1).

[6] Larger firms are more likely to disclose their emissions (Appendix Figure A2). The merged dataset is fairly representative across countries relative to World Bank estimates of aggregate emissions. Industrial emissions are somewhat over-represented relative to sectoral estimates produced by the World Resources Institute (Appendix Figure A4).

fications, the North American Industry Classification System (NAICS), and the Global Industry Classification Standard (GICS), assign firms to their main industry according to their primary business activities. The final one is a text-based industry classification developed by Hoberg and Phillips (2010, 2016) for listed US firms. This classification captures which firms compete with each other based on firms' own disclosures.[7]

We estimate the age of capital stocks and productivity at the firm level. Our estimate of the age of capital parallels the perpetual inventory method for estimating the size of capital stocks. We weigh all past investments (after accounting for depreciation) by how many years ago they took place, and divide by the sum of undepreciated investments.[8] As we do not have information on product-level prices, we estimate TFP from revenue data as in Asker et al. (2014).[9]

For a small subset of the US manufacturing firms in the sample (23 firms), we can access data on management practices from the World Management Survey (Bloom and Van Reenen, 2007; Bloom et al., 2012). The survey captures factors that are important for efficiency for the goods or services offered by each firm based on consensus among consultants and industry experts (Scur et al., 2021). We use estimates of R&D cost differentials due to US state tax credit from Lucking (2019).

3 Heterogeneity in Emission Intensity

This section documents the extent of firm-level heterogeneity in emission intensities within countries and industries. This heterogeneity is large and important: improvements in the environmental performance of laggard firms—i.e., firms with high emission intensities relative to industry-country peers—could significantly reduce total emissions.

The heterogeneity of firms' emission intensities within industries is large, comparable to or larger than heterogeneity in total factor and labor productivity. Our measure of emission intensity is the log of CO2 emissions (scope 1 plus scope 2) over revenues (megatons per million of USD revenue) in 2019. We extract residuals after control-

[7] Hoberg and Phillips (2010, 2016) provide both a distance measure between each pair of different firms in the sample and also a partition of the sample in groups of firms competing with each other—akin to the concept of industries in standard classifications. We rely on the latter.

[8] While we do not directly observe vintages of capital goods, our sample consists of large listed firms that generally purchase the newest vintage (Ma et al., 2022).

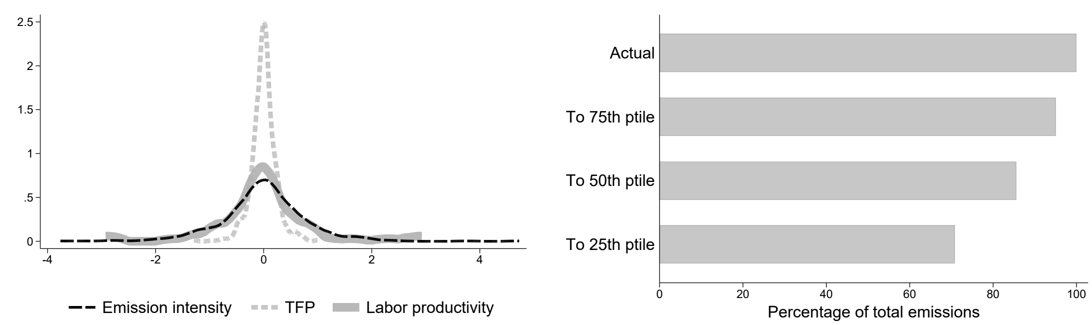
[9] This approach uses input expenditure shares to inform estimates of production functions.

ling for country × industry (4-digit SIC) fixed effects.[10] The distribution of residuals is plotted in Panel (a) of Figure 1 and shows large heterogeneity. For instance, the difference between the 90th and the 10th percentile—within the same industry and country group—is 1.85 log points, which translates into 6.37 times larger emissions per unit of revenue.[11] These magnitudes are substantial relative to heterogeneity in productivity: the 90-10 percentile difference of emission intensities is similar to the one for labor productivity (revenues over wage bill), which is 1.56 log points, and much larger than for revenue-based TFP, which is 0.51.[12]

Figure 1: Hetereogeneity in Emission Intensity Within Industry and Country

(a) Distributions

(b) Counterfactuals within industry and country



Notes: Panel (a) plots the kernel densities of the firm-level log of emissions intensity (measured as emissions over revenues), of (revenue) TFP, and of labor productivity (measured as revenues over wage bill), after controlling for industry × country fixed effects. Panel (b) illustrates the counterfactual emissions that we would observe (relative to a value of 100 for actual emissions) if every firm with emission intensity above the Xth percentile of the emission intensity distribution within the same country-industry group, saw its emission intensity reduced to that value. Only industry-country groups with at least 4 firms are included in panel (b). 4-digit SIC industry classification and 2019 data is used. Finance, insurance, real state, public administration, utilities, railroad transportation, and local and interurban passenger transit sectors are excluded from the calculation.

A simple back-of-the-envelope exercise shows that heterogeneity in emissions could have aggregate implications: a counterfactual in which firms with the worst environmental performance improve would entail significantly lower total emissions. Specifically, the exercise calculates how total emissions would change if every firm had emission

[10]We focus on 2019 to abstract from the potential effect of COVID. However, the results are robust if we focus on later or prior years.

[11]The heterogeneity is present both in advanced and in emerging markets and developing economies (Figure A5, Panel (a)). Interestingly, firms headquartered in countries with more stringent environmental policies have lower emissions intensities than other firms in the same industry (Figure A5, Panel (b)).

[12]These large differences in emission intensities are present in both advanced and emerging markets and developing economies (Panel (a) of Figure A11).

intensities at least as low as a particular percentile in their industry-country group, holding each firm's output constant. Panel (b) of Figure 1 shows the results of this exercise performed for different percentiles of emission intensities. With hypothetical improvements to the 25th percentile, aggregate emissions would fall by 33%. This suggests that improving the technology and production processes of laggard firms—even among existing technologies in each industry and country—can play an important role in reducing emissions.

This back-of-the-envelope exercise exogenously assigns emission intensities from greener to browner firms, holding firms' output constant. It does not consider whether such outcomes are feasible, which policies can achieve such gains, or at what cost. These considerations are explored in section 5 through the lens of a quantitative model.

4 Emission Intensity and Firm Characteristics

Why is heterogeneity in emission intensity so large? This section investigates the association between firm emission intensities and observable characteristics of the the production technology.

4.1 The Role of Capital-Embedded Technologies and Intangible Investments

The raw data shows that firms with higher emission intensity operate older physical capital stocks, have a lower share of intangible assets, and lower TFP (Figure 2).

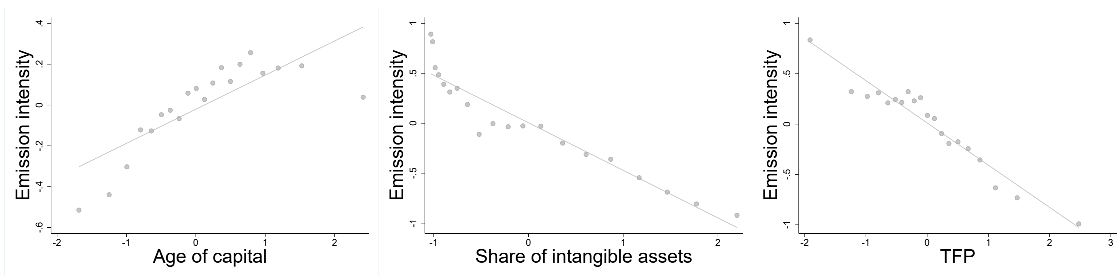
To control for differences across industries, countries, and firms size, and to restrict attention to the variation of interest, we estimate the following fixed effect specification:

$$log(EI_{i,t}) = \phi_{c(i),l(i),t} + \boldsymbol{X}_{i,t}\beta + \boldsymbol{W}_{i,t}\gamma + \epsilon_{i,t} \tag{1}$$

where $EI_{i,t}$ is the emission intensity of firm i in year t, $\phi_{c(i),l(i),t}$ is a set of year-specific fixed effects for i's country and industry, $\boldsymbol{X}_{i,t}$ are firm characteristics of interest, $\boldsymbol{W}_{i,t}$ is a set of controls, and $\epsilon_{i,t}$ is an error term. In our baseline, emission intensity is calculated as Scope 1 and 2 emissions scaled by revenues. For ease of interpretation, all variables are standardized to have mean zero and variance of one. To avoid capturing mechanical correlations, we normalize emissions by lagged revenues while the independent

Figure 2: Emission Intensity, Age of Capital, Intangible Capital, and Productivity

(a) Age of capital (b) Intangible assets (c) Productivity



Notes: The figure displays binned scatter plots of emission intensities (the logarithm of emissions over revenue) against the age of capital (panel a), the intangible share of assets (panel b), and the logarithm of revenue productivity (panel c) of the firm. All variables are standardized. Finance, insurance, real state, public administration, utilities, railroad transportation, and local and interurban passenger transit sectors are excluded from the calculation.

variables, when calculated relative to size, are normalized by total assets.[13] We include log assets as a control, to proxy for size and to avoid capturing decreasing returns to scale rather than the use of different technologies.[14]

Adoption of technologies embedded in newer vintages of physical capital and intangible investments in improving productivity are associated with firms' emission intensities *within* industries and countries (Table 1). First, we find that firms with older physical capital stocks emit more, relative to their size, than other firms in the same industry-country group (column 1). A one standard deviation increase in the age of capital is associated with 0.03-0.06 standard deviation higher emissions per unit of revenue. This suggests that legacy machines and production processes lead to higher emissions. Second, we show that increases in the share of intangible capital to total capital is associated lower emissions per unit of revenues (column 2). Finally, firms with higher TFP have lower emission intensities (column 3). Our results document a novel association between firm emission intensities and observable characteristics of the the production technology.

All correlations are robust to a specification that includes all independent variables

[13] If emissions intensities were calculated using contemporaneous revenue, potential measurement error could lead to a mechanical correlation, e.g., with TFPR, which also uses contemporaneous revenue for its calculation.

[14] Regressions only include country-industry-years with more than one observation. This restriction reduces the sample of firm-years in Table 1 columns (1-4), e.g., from nearly 14,000 to about 6,500 observations.

together (column 4). This mitigates concerns that individual coefficients may be driven by omitting the other variables.

Table 1: Emissions and Firm Characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Emission Intensity (Log emissions / revenue(t-1))				Emissions over Energy (Log emissions / energy)			
Age of capital	0.05***			0.03**	0.10***			0.10***
	(0.01)			(0.01)	(0.02)			(0.02)
Share intangibles		-0.17***		-0.13***		-0.00		-0.01
		(0.01)		(0.01)		(0.03)		(0.03)
TFP			-0.20***	-0.16***			0.01	0.02
			(0.01)	(0.01)			(0.03)	(0.03)
Log(assets)	0.04***	0.08***	0.13***	0.14***	-0.07**	-0.06**	-0.06**	-0.07**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)	(0.03)
N	6,534	6,534	6,534	6,534	2,690	2,690	2,690	2,690
R^2	0.80	0.81	0.82	0.82	0.51	0.51	0.51	0.51
Adj-R^2	0.70	0.71	0.72	0.73	0.23	0.22	0.22	0.23
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. By including only industry × country × year groups with more than one firm, our sample size is reduced from 13,947 to 6,534 in columns (1-4) and from 7,215 to 2,690 in columns (5-8). * $p < .1$, ** $p < .05$, *** $p < .01$

The magnitudes of these coefficients are economically significant: bringing firms closer to the technological frontier could have a meaningful effect on aggregate emissions. A back-of-the-envelope calculation similar to the one presented in section 3 finds that if all firms had physical capital vintages in the newest quartile, total emissions would fall by 7%, while if all firms were in the top quartile of intangible asset shares, total emissions would fall by 9%.[15]

We next decompose reductions in emission intensities into decreases in emissions per unit of energy consumed and declines in energy consumed per unit of revenue. More productive firms require less inputs, including energy, to produce a given amount of output. Firms may also be able to emit less holding the quantity of inputs fixed if, for example, they use greener energy sources. To help separate between these channels, we investigate how the age of physical capital and the share of intangible assets relate to emissions per unit of energy consumed.

[15] Results using 2019 data are presented in graphical form in Figure A6.

Our decomposition shows that capital embedded technologies are green-biased: firms with newer physical capital stocks emit less per unit of energy used (columns (5-8) in Table 1). The result suggests that newer capital facilitates the use of cleaner sources of energy. This could reflect greater reliance on electricity than on fossil fuel burning on site, allowing easier use of renewable energy sources. In contrast, firms with a higher share of intangible assets do not emit less per unit of energy used: better environmental performance is driven by lower consumption of inputs per unit of output.

4.2 Robustness

In this section we discuss several robustness exercises of the results presented in Table 1. These additional results help address a range of concerns, including whether we compare sufficiently similar firms, and which measures best proxy for the two key firm-level characteristics of interest. We also present evidence about management quality for a small sub-sample.

Industry classification. An important concern regarding our empirical results relates to industry classification. Our baseline empirical specification relies on the most granular industry classification available in our data: the 4-digit SIC industry classification. However, this classification remains imperfect and may mask heterogeneity in the products produced by the firms we classify as belonging to the same industry and country.

To mitigate such concerns, we show that our results remain similar when using different industry classifications. Specifically, we re-estimate Equation 1 by changing either the classification system or the granularity of the industry considered. Results are presented in Table 2. Moving from column (1) to (3) we observe that the estimated coefficients are stable when we change the granularity of the SIC industry classification from 4 to 2 digit.[16] The same stability is observed comparing columns (4) to (5) and (6) to (7), which refer to 2 and 4 digit GICS and NAICS classification systems. Our results are both qualitatively and quantitatively similar regardless of the classification system adopted.

Another concern with traditional industry classifications—like SIC or NAICS—is

[16]To facilitate comparison across columns, we keep the sample constant across columns that differ only because of granularity of the fixed effects but rely on the same classification system.

that they rely on pre-determined industry descriptions. Such classifications imperfectly capture economic boundaries reflecting product substitutability. Moreover, boundaries between markets can shift as new products and technologies change the competitive landscape. We therefore consider text-based industry classifications—derived from listed US companies' regulatory filings—that aim to capture which firms actually compete with each other (Hoberg and Phillips, 2010, 2016). Our results are robust to using this industry classification, as presented in column (8) of Table 2.[17]

Table 2: Emission Intensity and Firm Characteristics: Alternative Industry Classifications

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Emission Intensity (Log emissions / revenue(t-1))							
Age of capital	0.03**	0.03**	0.03***	0.06***	0.07***	0.03***	0.03***	0.05**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Share intangibles	-0.13***	-0.12***	-0.16***	-0.21***	-0.22***	-0.11***	-0.17***	-0.18***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.02)
TFP	-0.16***	-0.16***	-0.22***	-0.14***	-0.17***	-0.19***	-0.28***	-0.15***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)
Log(assets)	0.14***	0.13***	0.15***	0.14***	0.17***	0.15***	0.17***	0.08***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)
N	6,534	6,534	6,534	12,698	12,698	7,856	7,856	1,372
R^2	0.82	0.81	0.75	0.67	0.60	0.81	0.65	0.74
Adj-R^2	0.73	0.72	0.68	0.60	0.54	0.73	0.60	0.65
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry classification	SIC4	SIC3	SIC2	GICS4	GICS2	NAICS4	NAICS2	HP

Notes: Industry classification: SIC4 = 4-digit Standard Industrial Classification; GICS4 = 4-digit Global Industry Classification Standard; NAICS4 = 4-digit North American Industry Classification System; HP = Hoberg-Phillips 500. All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Energy, utilities, finance, and public sectors are excluded from the calculations. * $p < .1$, ** $p < .05$, *** $p < .01$

Alternative proxies for variables of interest. An additional challenge is that empirically capturing our objects of interest—newer capital-embedded technologies, investments in rising productivity, and production efficiency—is inherently difficult, given the large span of industries and countries covered by our sample. To mitigate this concern, we repeat the empirical analysis with alternative proxies. Results are similar to the baseline, as reported by Table A3, if we use the age of the firm to proxy for newer capital-

[17] Table A2 shows that results for emissions scaled by energy are also robust to alternative industry classifications.

embedded technologies, research and development (R&D) expenditures to proxy for investments in rising productivity, and profitability to proxy for production efficiency.[18]

Additional robustness tests. Large firms may differ from small firms in important ways: they may be older, with both older workforce and physical capital stocks, and may have more inertia preventing the adoption of greener production processes. Columns (1) to (4) in Table A5 show that our results are robust to including only large firms in the regressions, addressing these concerns. Columns (5) to (8) reveal that our results are robust to the inclusion of several financial controls (lagged leverage, liquidity, and capitalization ratios, and market share). This exercise mitigates the concern that our results may be driven by financial frictions or corporate finance decisions which may impact both technology adoption and emissions.[19] Columns (9) to (12) show that the results are robust to removing 2020 and subsequent years, and hence are not driven by the COVID pandemic. Columns (13) to (16) illustrate that results are similar when we focus only on scope 1 emissions, which may be easier to measure for the reporting firms.[20] Table A7 shows that results are robust to separately focusing only on firms headquartered in AEs or EMDEs. Columns (1-4) in Table A8 exhibit that our results are robust to computing emission intensities as emissions over total assets, rather than revenues, to mitigate the concern of a potential mechanical correlation between emission intensities and productivity estimated from data on sales. Columns (5-8) in Table A8 shows that our results are robust to utilizing value added rather than revenues to calculate emission intensities, which may better reflect the extent of value and production generated by the firm.[21] Finally, firm-specific shocks may be correlated over time. Table A9 shows that results are consistent when clustering standard errors at the firm level.

Management practices. To provide further evidence that improved production processes help lower emissions per unit of output, Table A10 shows that firms with higher management scores, as captured by the World Management Survey (WMS) (Bloom and Van Reenen, 2007), have lower emission intensities relative to other firms in the

[18]Table A4 shows that results for emissions scaled by energy are also robust to alternative measures of firm technology.

[19]For this reason, the model proposed in section 5 abstracts from such frictions.

[20]Table A6 shows robustness for emissions scaled by energy.

[21]Value added is computed as in Karabarbounis and Macnamara (2021).

same industry. Because the WMS captures managerial practices mostly related to the efficiency of production processes, this result mitigates the concern that the positive correlation between TFP and emission intensities is solely driven by heterogeneous markups across firms.[22] The positive correlation between the age of the capital stock and emissions per unit of energy also contributes to mitigate this concern (Table 1).

4.3 Instrumental Variable Strategy

The previous subsection documents a robust association between firm emission intensity and technological factors. In this subsection, we provide evidence based on instrumental variables suggesting that these associations are likely to be driven by a causal impact of technological factors on emissions.

We begin by investigating whether policy-induced heterogeneity in R&D investments impacts firms' environmental performance. Corporate investments in R&D are a major way to accumulate intangible capital and improve productivity. However, firms investing more in R&D may be different in other ways: e.g., they may have more skilled or forward-looking executives, who may also care more about the environmental impact of their company. To overcome such endogeneity concerns, we utilize Lucking (2019)'s measure of differences in R&D cost for manufacturing firms by US states due to differences in tax credit policies as an instrument for R&D expenditures.[23] We use the state tax credit in the headquarter location to proxy for the actual state tax credit faced by firms. Table 3 presents the results. Column (1) shows an OLS regression of firm emission intensity on R&D (normalized by revenues) while controlling for industry times year fixed effect and for firm size, for the sample of US manufacturers. Firms that spend more on R&D also emit less per unit of revenue. Column (2) presents the first stage of the IV strategy, which is a regression of firm R&D on the cost of R&D due to state tax credit. We find that firms in low-R&D cost states invest more in R&D. Column (3) shows that firms in low-cost R&D not only spend more in R&D, but also have lower

[22] Measures of productivity constructed using revenue data raise the concern that a higher value—greater revenue after accounting for input expenditures—may result from increased market power rather than improved production efficiency. Such market power, reflected in increased revenues for a given amount of inputs used in production, would also lead to a lower emission intensity. Consequently, the positive correlation observed between our productivity measure and emission intensities may stem from firm-level market power.

[23] In fact, policies to promote R&D investments by offering subsidies or tax credits are common. A large literature has aimed at evaluating the impact of public R&D incentives (Becker, 2015).

emission intensity, indicating a causal role of R&D on emissions. Column (4) presents a two-stage least square model where R&D expenditure is instrumented by cost of R&D credit. We find a negative and statistically significant coefficient for R&D, indicating that R&D is effective in lowering emission intensity.

Table 3: Emission Intensity and R&D

	(1) Emission Intensity (OLS)	(2) R&D (First stage)	(3) Emission Intensity	(4) Emission Intensity (2SLS)
R&D	-0.231***			-2.310***
	(0.0570)			(0.884)
Cost of R&D		-11.13*	24.83***	
(due to Tax-credit)		(6.090)	(8.715)	
N	1,264	1,264	1,264	1,264
R^2	0.821	0.891	0.820	-0.068
Industry × Year FE	Yes	Yes	Yes	Yes
		90% Confidence Intervals (Robust to Weak Instruments)		
Wald CI:				[-3.76,-.86]
Anderson-Rubin CI:				[-5.19 ,-1.22]
		95% Confidence Intervals (Robust to Weak Instruments)		
Wald CI:				[-4.04,-.58]
Anderson-Rubin CI:				[-6.83 ,-1.06]

Notes: Regressions include only US manufacturing firms. The cost of R&D due to US state tax credit is measured by Lucking (2019) and applied to the state where each US manufacturing firm is headquartered. All regressions add as a control variable the size of the firm (level of assets measured in logs). For column(4), the first stage F-statistic is 3.396 (Montiel-Pflueger). Standard errors in parentheses, clustered at the state level. * $p < .1$, ** $p < .05$, *** $p < .01$

Weak instrument techniques support the conclusion that R&D improves environmental performance. The coefficient in column (2) of Table 3 is different from zero only at the 10% confidence level, suggesting that state headquarter is a noisy proxy for the company's establishment location. Consequently, our measure of R&D costs is a weak instrument for R&D investments, as indicated by the first stage F-statistic which is below 4. Recent econometric advancements (Andrews et al., 2006; Isaiah et al., 2018; Pierri and Timmer, 2022) allow us to estimate confidence intervals which are robust to the weak instrument problem (but not to estimate robust point estimates). The Wald and Anderson-Rubin confidence intervals—which are optimal in this setting (Isaiah et al., 2018)—reported at the bottom of Table 3 exclude zero. This means that the instrumental variable approach excludes a null impact of R&D on emission intensity.

Measurement error could also bias some of our estimates. Specifically, our measure the age of capital stock is based on the timing of firms' investments but we have no information on the specific equipment purchased by each firm, which could be older. We therefore consider instrumenting the age of capital stock with firms' growth rates in recent years. Two firms of the same size may have physical capital stocks with very different ages depending on whether they achieved that size in a short or long period. Firms that grow faster are likely to have newer capital. The instrument is valid under the assumption that given a high-growth firm and a low-growth firm *of the same size and same TFP*, environmental performance is affected only by the age of their capital stocks. Consistent with significant attenuation bias in our OLS specifications, Table A11 and Table A12 suggest a causal relationship between the age of capital stock and emission intensity significantly larger than implied by OLS.

These instrumental variable results provide evidence supporting a causal impact of the adoption of newer physical capital-embedded technologies and intangible investments to raise productivity in improving firms' environmental performance. The IV coefficients are significantly larger than the OLS ones, consistent with difficulties in measuring the exact age of capital from balance sheet data.

5 A Model of Capital Vintage and Knowledge Intensity

To rationalize the empirical findings and investigate their implications for mitigation policies, we propose a multi-sector heterogeneous-firm general equilibrium model incorporating both entry and exit. We embed a Hopenhayn (1992) framework in a multi-sector setting and generalize the firms' emissions and production technologies to include capital vintage and intangible knowledge accumulation.

5.1 Setting

There is a finite number of countries indexed by $j \in \{1, ...J\}$. We abstract from trade in goods and assets across countries. Time is discrete and runs to infinity, $t = 1, 2, ...$. When no confusion results, we omit the country and time subscripts.

Households' Preferences. In each country, the preferences of the representative household over streams of consumption bundles, $\{\mathscr{C}_t\}_{t=1}^{\infty}$, are described by $\mathscr{U} = \sum_{t=1}^{\infty} \left(\frac{1}{1+\rho}\right)^t U(\mathscr{C}_t)$ where $U(.)$ is a strictly increasing and concave utility function and ρ is the discount rate. In each period, the consumption bundle is made of goods from S different sectors $s = 1,...,S$. In each sector s, a set of $\mathscr{S}_s$ of firms in monopolistic competition supplies differentiated varieties indexed by $i \in \mathscr{S}_s$. Households have Cobb-Douglas preferences over sectors and constant elasticity of substitution preferences over varieties within each sector s, $\mathscr{C}_t = \prod_{s=1}^{S} C_{st}^{\beta_s}$ with $C_{st} = \left[\sum_{i\in\mathscr{S}_s} \xi_{si}^{\frac{1}{\sigma}} c_{sit}^{1-\frac{1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$ where ξ_{si} is a taste shock for the good produced by firm i in sector s, σ is the constant elasticity of substitution across varieties within a sector, and β_s is the expenditure share of household income on sector s, with $\sum_s \beta_s = 1$.

Taking prices of all goods as given, households seek to maximize their utility subject to their budget constraint, given by $\sum_{s=1}^{S} \sum_{i\in\mathscr{S}_s} p_{sit} c_{sit} + B_{t+1} \leq w_t L + T_t + mN_t + \Pi_t + (1 + r_t)B_t$ where w_t is the nominal wage, L is the households' exogenous supply of labor, T_t are transfers net of taxes from the government, B_t are financial assets, r_t is the one-period interest rate, and Π_t denotes aggregate profits of all firms rebated in a lump-sum way to households. Natural resources used to produce energy and denoted by N_t belong to the representative household, who sells them to firms at an exogenous price m. For simplicity, they are supplied fully elastically.

Utility maximization at time t leads to the following demand for firm i in sector s.

$$c_{sit} = \xi_{si} \left(\frac{p_{sit}}{P_{st}}\right)^{-\sigma} C_{st} \quad \text{with} \quad C_{st} = \beta_s \frac{P_t \mathscr{C}_t}{P_{st}} \tag{2}$$

where the industry-s and the overall consumer price indexes are given by

$$P_{st} = \left(\sum_{i\in\mathscr{S}_s} \xi_{si} p_{sit}^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \quad \text{and} \quad P_t = \Pi_{s=1}^{S} \left(\frac{P_{st}}{\beta_s}\right)^{\beta_s}. \tag{3}$$

Firm's Production and Emissions Technologies. Each firm $i \in \mathscr{S}_s$ produces its own product, which it sells to households, using a Cobb-Douglas technology that is common across firms within a given sector s and country j. Motivated by our empirical findings, production combines the firm's intangible knowledge ω_{si}, physical capital k_{vsi} of vintage v_{si}, energy n_{si}, and labor ℓ_{si}. The production function in sector s is given by

$$y_{si} = \omega_{si} (v_{si} k_{vsi})^{\kappa_s} n_{si}^{\eta_s} \ell_{si}^{\lambda_s}. \tag{4}$$

The technology for firm emissions is also motivated by our empirical evidence and novel relative to the literature. Specifically, the firm's emissions depend on three terms. First, on how much energy it consumes in production, n_{si}, which includes both energy purchased externally and produced within the firm. Second, on the quality of vintage it uses, v_{si}: higher-quality vintages allow firms to decrease their emissions by using or purchasing cleaner sources of energy. This second term captures the green bias of newer capital vintages. Third, on factors common to all firms within a country and sector, such as the energy mix of the electricity grid.[24] Denoting the latter as ϕ_s, a firm's emissions are given by[25]

$$e_{si} = \phi_s n_{si} v_{si}^{-\epsilon_v} \tag{5}$$

Importantly, the production and emission technologies in Equation 4 and Equation 5 are consistent with the stylized facts shown in section 4. Firms with higher intangible investments and newer capital vintages emit less per unit of output, and capital vintages are green biased. We formalize the consistency of the model with our stylized facts at the end of this section.

Firm's Vintage and Investment in Tangible Capital Decisions. Each period, firms have the opportunity to choose a vintage of capital and invest to expand their stock of physical capital. Vintages are indexed by v and the set of available vintages—denoted $\mathcal{V} = \{1, ..., V_s\}$—is assumed to be exogenous as in Garcia-Lembergman et al. (2023), which is consistent with the medium-run horizon of our policy counterfactuals (5 to 10 years). We define v as the efficiency unit per unit of capital. Vintages are thus ranked by their efficiency and $v_s = V_s$ is the best vintage in sector s. When mapping the model to the data, we will relate the efficiency v_s to the age of the capital stock and discipline this relationship with the extent to which newer capital stocks are more emission-efficient. There are markets for each capital vintage. Denoting q_{v_s} the market price, $x_v q_{v_s}$ is the cost of x_v units of a capital vintage v_s.

[24]While we exclude utilities and energy companies from the sample used for the regressions and estimation of the model, the energy produced by these companies and sold to the corporate sector, and the implied emissions, are captured by the demand of energy and scope two emissions in our counterfactual exercises.

[25]Firms emit greenhouse gases both directly, through production processes within the boundaries of the firm (scope one emissions), and indirectly, through energy purchased from other companies (scope two emissions). Scope one and scope two emissions are both quantitatively important, although with some heterogeneity across industries (see Appendix Figure A3), and our analysis encompasses both types.

The decision to upgrade capital vintages is subject to two investments frictions, capturing realistic obstacles firms face when greening their production processes. First, we assume that it is prohibitively costly to operate different vintages simultaneously. As a result, a firm that updates its vintage needs to replace the entire stock of capital. Second, building on the findings of Kermani and Ma (2022) that most of the value of the capital stock is firm specific, we assume that if a firm decides to upgrade, and invest in a newer capital stock, it cannot recover the full value of its old vintage of capital on secondary markets. Instead, it can recover only a fraction χ of the value of the capital. When choosing which vintage of capital to use and how much to invest in capital of this vintage, firms therefore trade off the opportunity cost of retiring a productive asset with the profit gains from getting more productive and expanding their business. Taken together, these two assumptions imply that the decision to upgrade one's capital stock is costly and lumpy, two well-documented facts.[26] Finally, every period capital depreciates at rate δ.

Firm's Investment in Intangible Capital. Firms differ in the efficiency with which they combine their inputs. Firm i's intangible knowledge ω_{si} is the product of internal investments made by the firm and spillovers from intangible investments made by other firms in the same sector and country. The latter captures the fact that knowledge diffuses across firms within each industry through workers, sharing of information, and the purchase of patents. More specifically, we follow Romer (1986) and assume that ω takes the following form

$$\omega_{si} = A_s^{\theta_s} a_{si} \tag{6}$$

where A_s denotes the aggregate intangible knowledge by all firms in industry s, and $\theta_s \in (0,1)$ is the strength of the externality. The aggregate stock of intangibles is the sum of knowledge capital embedded and produced in each firm, $A_s = \sum_i a_{si}$.

Firms hire workers ℓ_a to improve their productivity with the following accumulation

[26] See, for example, Winberry (2021) for a recent analysis of the implications of firm-level fixed costs of investment. Closer to our paper, Finkelstein Shapiro and Metcalf (2023) assume a fixed cost of switching to a green technology.

technology

$$a'_{si} = (1-\delta_a)a_{si} + \left(\frac{\ell_a}{\gamma_{si}}\right)^{\alpha_s} \tag{7}$$

where the prime superscript refers to the following period, δ_a denotes the depreciation rate of knowledge capital, and γ_{si} is the knowledge accumulation efficiency parameter. The latter represents the cost in terms of labor of increasing the productivity of the production process, a. An alternative interpretation is that it represents the cost of increasing the quality of the product. It is firm-specific, capturing differences across firms in productivity for generating ideas that improve their production processes. Firms learn about their knowledge accumulation efficiency after entering the market, and γ is drawn from a cumulative distribution $G_s(\gamma)$ which is country and industry-specific.

In the rest of the paper we will assume that the elasticity of knowledge creation to labor, α_s, is equal to one minus the sum of the exponents on inputs in the output technology (4), $\alpha_s = 1-(\kappa_s+\eta_s+\lambda_s)$. This assumption is analogous to the more traditional assumption of constant returns to scale.

Government Interventions: Carbon Taxes, Subsidies and Feebates. We consider four taxes or subsidies. First, there is a carbon tax, with rate τ_e, which is proportional to emissions, e.[27] Second, there is a rebate proportional to sales τ_y, or a negative sales tax, which we will use in the design of the carbon feebate. Third, there is a vintage-specific subsidy τ_v, which results in an after-subsidy unit price of capital of $q_v(1-\tau_v)$. A subsidy to the newest and most productive capital vintage means that $\tau_v = 0$ for $v < V$ and $\tau_V > 0$. Finally, there is a subsidy to intangible investments toimprove total factor productivity, which we denote τ_a. The government budget is balanced in every period:

$$T = \sum_{s=1}^{S}\sum_{i\in\mathscr{S}_s}\left(\tau_e e_i - \tau_y p_i y_i - \sum_{v_s}\tau_{v_s} q_{v_s} x_{v_s i} - \tau_a w \ell_{ai}\right) \tag{8}$$

The Incumbent Firm's Problem. After having decided which vintage to use, how much to invest in physical capital, and how much investment to make to improve intangible

[27] It is possible to replicate the allocation implied by a carbon tax with an equivalent carbon trading scheme in which firms are obligated to buy permits for all emissions, and in which the government earns the receipt of the sale of permits.

knowledge, firms choose how much labor for production ℓ and energy n to use as well as the price of their good. Whenever they operate, firms have to pay a fixed cost κ_f every period. Taking the wage w, the price of energy m, and the prices of capital goods $\{q_v\}_{v=1}^{V}$ as given, a firm entering the period with a stock of capital k_v of vintage v, knowledge accumulation efficiency γ, a stock of intangible knowledge a, and consumers' taste ξ faces the following dynamic profit-maximization problem

$$\mathcal{V}_s(a,k_v,v,\gamma,\xi) = \max_{v',k'_{v'},\{x_{\tilde{v}}\}_{\tilde{v}=1\dots V_s},\ell_a,a'} \Big\{ \pi_s(a,k_v,v,\gamma,\xi) - \sum_{\tilde{v}=1}^{V_s} q_{\tilde{v}} x_{\tilde{v}} (1-\tau_{\tilde{v}}) \left(\mathbb{1}_{x_{\tilde{v}}\geq 0} + \chi \mathbb{1}_{x_{\tilde{v}}<0}\right) \\ - w(1-\tau_a)\ell_a + \frac{1}{1+r}\mathcal{V}_s(a',k'_{v'},v',\gamma,\xi) \Big\} \tag{9}$$

$$\pi_s(a,k_v,v,\gamma,\xi) = \max_{p,\ell,n} \left\{ py(1+\tau_y) - w\ell - mn - e\tau_e - \kappa_f \right\} \tag{10}$$

subject to the demand schedule (2), the production technology (4), the emission technology (5), the law of motion for intangible capital (7), and the law of motion for capital (of each vintage) given by:

$$\begin{aligned} k'_{v'} &= (1-\delta)k_{v'} + x_{v'} \\ k'_v &= 0 \qquad\qquad \text{if } v' \neq v \end{aligned} \tag{11}$$

Equation (9) describes the dynamic decisions taken by the firm—the investments in tangible and intangible capitals and the vintage upgrade decisions—and the resulting value function. This value function is the sum of current profits minus the cost of investing in capital goods and intangible knowledge, plus the recovered retired capital if the firm switches its capital vintage, plus the continuation value discounted at the risk-free rate r. Equation (10) captures the static optimal input decision of the firm, choosing prices and spending on labor and energy to maximize current profits.

Entry and Exit. The expected discounted sum of profits of a new entrant before entry is given by $\mathbb{E}_{G_s}\mathcal{V}_s(a,k_{V_s},V_s,\gamma,\xi)$, where the expectation is taken under the sector-specific joint distribution of knowledge accumulation efficiency and consumers tastes $G_s(\gamma,\xi)$. Potential entrants must pay an entry cost κ_e before learning about their knowledge accumulation productivity γ and their consumers' tastes ξ. They enter if they expect to make positive profits, namely if and only if

$$\mathbb{E}_{G_s}\left[\mathcal{V}_s(0,0,.,\gamma,\xi)\right] > \kappa_e \tag{12}$$

Incumbent firms decide whether to exit each period. Because they have to pay the fixed operating cost κ_f every period, it is possible for a firm to make negative profits. As a result, an incumbent exits if the present discounted value of profits is negative, even after considering updating its vintage of capital, downsizing or expanding. On the contrary, an incumbent decides to stay if and only if

$$\mathcal{V}_s(a, k_v, v, \gamma, \xi) \geq 0 \tag{13}$$

Production Technology for Capital Goods. Capital goods are produced by a competitive sector that uses labor with a linear technology. These price-taking firms maximize profits and solve the following problem

$$\max_{x_{v_s}, \ell_{v_s}} q_{v_s} x_{v_s} - w\ell_{v_s} \quad \text{subject to} \quad x_{v_s} = z_{v_s}\ell_{v_s} \tag{14}$$

Competitive markets imply that in equilibrium the price of capital goods is pinned down by the productivity of labor: $q_{v_s} = wz_{v_s}^{-1}$. In addition, the production of capital goods generates emissions. Contrary to the case of final goods, we cannot assume that emissions are a function of energy use and capital vintages, because we abstract from these two inputs. Instead we assume that the emission intensity (the ratio of emissions over revenues) is the same as in the rest of the economy.

The market clearing conditions and the equilibrium definition are given in Appendix A1.1.

5.2 Properties of the Equilibrium

We now characterize the optimal decisions of firms to shed light on the novel margins through which policies affect firm emissions we document in the empirical section 4. First, firms can choose to upgrade to a better vintage of capital, thereby economizing on energy and emissions. Second, they can change their intangible investments to increase their overall efficiency. Beyond these novel margins, firms can also deepen their capital intensity and adjust their variable inputs to reduce energy consumption.

We show analytically that this rich framework is consistent with the empirical evidence we present on the role of capital vintages and intangible investments. In the perspective of the counterfactual analysis of section 6, we also analyze how different mitigation policies affect each margin. Derivations and proofs can be found in Appendix A1.

Capital and Vintage Decisions. The first critical decision is whether to upgrade to a more productive vintage of capital and how much tangible capital to accumulate. We first consider the case of a firm keeping its current vintage and choosing how much to invest. Its optimal steady-state level of capital is given by

$$k_v = \left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a q_v}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{\Omega_s(v,\gamma,\xi,\tau_e)\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \tag{15}$$

where $\hat{\kappa}_s = \frac{\kappa_s}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}$.

Each climate policy affects the optimal capital stock of a firm, given by (15), differently. Since the optimal level of capital is decreasing in its price q_v, policies that subsidize the newest vintage of capital $\tau_V > 0$ will give an advantage to firms with this vintage and incentivize them to grow. In addition, these policies incentivize firms with a less productive vintage to upgrade by lowering the cost of adopting the newest vintage, a point to which we return below.

Policies that put a price on carbon, such as a carbon tax or a feebate, have ambiguous and heterogeneous effects on capital investment across firms. They incentivize firms to use less energy overall, and to increase their reliance on capital of any vintage. They also increase the relative cost of using capital of older vintages, thereby giving incentives to firms with these vintages to downsize.

Finally, subsidies for intangible investments lead to more investment in intangibles, and to disinvestment from physical capital, which leads to a lower stock of capital in equilibrium.

The second margin of response to policies is the possibility for firms to upgrade to a newer vintage of capital. This decision amounts to comparing the value of upgrading to the value of continuing production with the older vintage. The following lemma provides a sufficient condition for upgrading firms to always adopt the most productive vintage V_s and establishes that updating firms are the ones with the oldest capital vintages.

Lemma 1 (Vintage decision)**.** *Assume that the elasticity of z_v to v is strictly higher than* -1.

1. *If a firm updates its vintage, it upgrades to the best vintage V_s.*
2. *There exists a unique $\underline{v}_s$ such that a firm with v upgrades to V_s if and only if $v < \underline{v}_s$.*

The condition implies that v_s/q_s is increasing in v_s which in turn means that the newest vintage is always the optimal choice when a firm updates. Policies that lower the price of the newest vintage q_V through a subsidy to capital investment τ_V, give direct incentives to all firms with older capital vintages to upgrade since the value of upgrading (54) is increasing in τ_V. Carbon taxes and feebates also give incentives to upgrade, but indirectly through the price of energy. As we have discussed in the paragraph on energy use, firms with older vintages emit more and thus face larger cost increases when a carbon tax is implemented. Therefore, these firms have an incentive to upgrade in response to the introduction of a carbon tax.

Optimal Choice of Energy. We continue with the optimal consumption of energy given a stock of capital k_v of vintage v. It is given by

$$n = \Lambda_s(\xi) A_s^{\hat{\rho}} \left(\frac{\lambda_s}{w}\right)^{\hat{\lambda}_s} \left(\frac{\eta_s}{m + \tau_e v^{-\epsilon_v}}\right)^{\hat{\eta}_s + 1} (v k_v)^{\hat{\kappa}_s} \tag{16}$$

$$\text{with} \quad \Lambda_s(\xi) = \left[\frac{\sigma - 1}{\sigma}(1 + \tau_y)(\eta_s + \lambda_s) P_s (\xi Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma}{\sigma + (1-\sigma)(\eta_s + \lambda_s)}}$$

where $\hat{x} = \frac{x}{\frac{\sigma}{\sigma-1} - (\eta_s + \lambda_s)}$ for $x = \rho, \lambda_s, \eta_s$ and $\frac{\sigma}{\sigma-1} > (\eta_s + \lambda_s)$ which ensures that the optimal input decisions are well-defined. It is intuitive that the consumption of energy is increasing in the productive capacity of the firm, as measured by its capital stock k_v, and increasing in the elasticity of output to energy, η_s.

Climate policies affect the consumption of energy first and foremost through the price of energy, $m + \tau_e^{v - \epsilon_v}$, which includes the carbon tax. An increase in the price of energy leads firms to substitute away from energy, to rely relatively more on capital and labor, and to scale down their production.[28]

An increase in the price of carbon impacts firms differently. Firms operating older and less efficient vintages, which emit more CO2 per unit of energy consumed, are

[28]Given the assumption of a Cobb-Douglas production function, the elasticity of substitution across inputs, i.e., the elasticity of the ratio of inputs ℓ/n to their relative price $w/(m + \tau_e v^{-\epsilon_v})$, is one.

impacted more significantly. As a result, firms with less efficient vintages reduce their energy consumption to a larger extent. Additionally, the effect of a carbon tax varies across sectors: firms operating in sectors highly dependent on energy for production, those with high η_s, are also more affected. This results in more pronounced reduction of energy use in these energy-intensive sectors.

Optimal Investment in Intangibles. Another important margin of response is the ability to accumulate intangible knowledge. The optimal level of labor to invest in intangibles and the implied level of accumulated knowledge in steady state is given by

$$\ell_a = \left(\frac{\Omega_s(\upsilon,\gamma,\xi,\tau_e)\hat{\alpha}_s k_\upsilon^{\hat{\kappa}_s}}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a} \right)^{\frac{1}{1-\hat{\alpha}_s}} \quad \text{and} \quad a = \left(\frac{\ell_a}{\gamma}\right)^{\alpha} \frac{1}{\delta_a} \tag{17}$$

where $\Omega_s(\upsilon,\gamma,\xi,\tau_e)$ is the revenue-productivity of (physical and intangible) capital, since by definition $py = \Omega_s(\upsilon,\gamma,\xi,\tau_e) k_\upsilon^{\hat{\kappa}_s} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}}$. Its expression is given in Appendix A1.3. The revenue-productivity of capital $\Omega_s(\upsilon,\gamma,\xi,\tau_e)$ is increasing in υ and ξ, decreasing in γ, decreasing in the carbon tax τ_e, and it depends positively on the sectoral price index P_s and production Y_s.

As was the case for energy consumption, the decision to invest in intangibles depends on the scale of the firm, as measured by k_υ. Because intangibles accumulation relies on labor as its only input, it is negatively impacted by an increase in the wage rate w. Moreover, firms that are not efficient at accumulating intangibles, those with high γ, endogenously accumulate less and use other inputs relatively more, such as energy or raw labor.

It is clear from equation (17) that both subsidies to intangible investment τ_a and policies that directly target emissions τ_e give incentives to firms to scale up their intangible investments to improve their productivity and economize on energy. The decline in the consumption of energy is especially strong for firms using a vintage of capital of lower quality and for firms in sectors that rely more on energy, those with high η_s.

Optimal Pricing Decision. Firms compete monopolistically and have local market power to set the price of their variety. The optimal price is a constant markup over marginal cost. Given that this is not specific to our setting, we refer the reader to Appendix A1.3 for more details.

General Equilibrium Channels. At the firm level, policies affect emissions through changes in energy use, other variable inputs, intangible capital and capital intensity, and the quality of vintages used. But there are general equilibrium channels as well: market shares are reallocated across heterogeneous firms and production shifts across sectors. For example, sectors and firms that rely more on energy will shrink following an increase in the carbon tax, and those that rely to a larger extent on intangible capital will expand with a intangible investments subsidy. Within industries, firms that rely more on the newer capital vintage benefit from the subsidy for the newer vintage and grow at the expense of other firms. In addition, firms enter and exit endogenously. For example, a subsidy to the newest vintage increases profitability for new firms, a feebate stimulates entry, and a carbon tax may lead some firms to exit.

5.3 Consistency with Stylized Facts

In the following proposition, we show that the model is consistent with our empirical findings: emission intensity at the firm level is driven by the age of the capital stock, knowledge intensity, and size. In addition, productivity and emission intensity are related and driven by the same factors. Through the lens of the model, the firm's vintage quality (v)—which is closely related to the capital's age—and its knowledge accumulation efficiency ($1/\gamma$)—which shapes its knowledge intensity—are two underlying drivers of both its emission intensity and productivity.

Proposition 1. *In steady-state, holding capital k and tastes ξ constant, firms with newer vintages (v) or/and higher knowledge accumulation efficiency ($1/\gamma$) emit less per unit of output:*

$$\ln\frac{e}{y} = \ln c_{st} - (\zeta_{ev1} + \epsilon_v)\ln v + \zeta_{ev2}\ln(m + \tau_e v^{-\epsilon_v}) + \zeta_{e\gamma}\ln\gamma - \zeta_{ek}\ln k + \zeta_{e\xi}\ln\xi \qquad (18)$$

with $\zeta_{ev1} = (\kappa + \alpha_s\epsilon_{qv})b_{es}$, $\zeta_{ev2} = \eta_s b_{es} - 1$, $\zeta_{e\gamma} = \alpha_s b_{es}$, $\zeta_{e\xi} = (1-\eta_s-\lambda_s)b_{es}$,$\zeta_{ek} = (\alpha_s+\kappa_s)b_{es}$ and $b_{es} = \big(\sigma + (\sigma-1)(\eta_s+\lambda_s)\big)$, and have higher TFP:

$$\ln TFP = \ln z_{st} + \zeta_{ev1}\ln v_i - \zeta_{ev2}\ln\left(m + \tau_e v^{-\epsilon_v}\right) + \zeta_{e\gamma}\ln\left(1/\gamma\right) + \zeta_{e\gamma}\ln k + \frac{1}{\sigma}\log\xi \qquad (19)$$

with $\zeta_{ev1} = \kappa b_e$, $\zeta_{ev2} = \eta b_{es}$, $\zeta_{e\gamma} = \alpha b_{es}$, and $b_e = 1 - \frac{1}{\sigma}$. c_{st} and z_{st} are common to all firms within a time period, country, and sector. Their full expression is given in Appendix

A1.

To understand the first result, recall that emissions over output can be decomposed into the product of emissions over energy consumed and energy over output. The quality of the capital vintage v, and knowledge accumulation efficiency $1/\gamma$, are positively related to energy efficiency, and the quality of the capital vintage v also reduces emissions per unit of energy (equation 5).

As can be seen in the second expression, the model suggests that the way to interpret the positive empirical association we find between TFP (estimated with revenues) and emission intensity is that both are positively shaped by the quality of the vintage v and the knowledge accumulation efficiency $1/\gamma$. Note that the relationship between environmental performance and size is more complex because size depends positively on a firm's vintage quality and knowledge accumulation efficiency but also on consumers' tastes.

6 Calibration

We now carefully calibrate the model for multiple countries to match the empirical distribution of firms, the importance of the new margins of response, and the green bias of capital-embedded technologies. We also match important country and sector-level moments. A small subset of the parameters are calibrated externally. The rest are estimated from the data.

6.1 External calibration

We begin by calibrating a number of parameters that can be set externally. These parameters are listed in Table 4. The time discount factor ρ, the depreciation rate of physical capital δ_k, and the elasticity of substitution across goods within sector σ, are all calibrated to standard values used in the literature. The depreciation rate of knowledge δ_a is calibrated following Doraszelski and Jaumandreu (2013). The fraction of the capital stock that can be resold by a firm upgrading χ, is calibrated to match the finding by Kermani and Ma (2022) that on average 65% of the capital stock is firm-specific, which implies $\chi = 0.35$. We calibrate the difference between the growth rate of vintage productivity and price to match the estimated value of 3.2% in Greenwood et al. (1997).[29] Finally, we assume that the utility function of the representative consumer U is linear, which implies a constant interest rate in equilibrium. This simplifies the computation of the transition path since the economy allocates all available resources towards the transition before reaching the new steady-state—a process which for most countries and most policies takes only one period.[30]

Table 4: Externally Calibrated Parameters

Parameter	Description	Value	Source
ρ	Discount rate	0.04	Standard
δ_k	Depreciation rate of capital	0.05	Standard
δ_a	Depreciation rate of knowledge	0.15	Doraszelski and Jaumandreu (2013)
σ	Elasticity of substitution	8	Standard
χ	Liquidation value	0.35	Kermani and Ma (2022)
$g_v - g_p$	Vintage productivity/price growth	3.2%	Greenwood et al. (1997)

6.2 Internal Calibration

The model's other parameters are estimated and can be split into four categories: those that are common to all firms in the world, to firms within a country, to firms within a country and a sector, and those that are firm-specific. Table 5 gives the full list.

We briefly summarize our calibration strategy here and we refer the reader to Appendix A2 for a detailed explanation. At the country and industry level, we calibrate the elasticity of utility to each sector-level good β_s, to match the share of sales of each sector separately for each country. While our sample of listed firms may not be representative of the whole corporate sector, we re-weight observations in order to match the share of each industry in each country. At the same level, the elasticity of output to its factors is identified using the assumption of constant returns to scale, the average sales and cost of goods sold, and the shares of costs going to labor, energy and research. Building on the literature, in particular Griliches (1992) and Bloom et al. (2013), we assume that the social returns to intangible knowledge are equal to its private returns, $\theta_s = \alpha_s$.

We target and match the IV estimates of both the elasticity of capital productivity and of emissions to vintage age. We assume that the productivity of vintages grows at

[29] Combined with our own empirical and model-consistent estimate of the growth rate of vintage productivity explained below, we can obtain the growth rate of vintage prices, which is otherwise difficult to observe.

[30] Another advantage of linear utility is that the net present value of consumption measures social welfare and is independent of specific assumptions regarding the intertemporal elasticity of substitution.

Table 5: Internally Calibrated Parameters and Firms' Characteristics

Parameter	Description	Granularity
g_v	Growth rate of vintage productivity	All countries
ϵ_v	Emissions elasticity to vintage	All countries
κ_f	Cost of operating	Country
ϕ^e	Average emissions per unit of energy	Country × Sector
κ_e	Cost of entry	Country × Sector
β	Expenditure share	Country × Sector
α	Knowledge elasticity to research	Country × Sector
ρ	Knowledge spillover	Country × Sector
κ	Capital elasticity of output	Country × Sector
η	Energy elasticity of output	Country × Sector
λ	Labor elasticity of output	Country × Sector
$G(\gamma,\xi)$	Distribution of initial parameters	Country × Sector
ξ	Consumers' taste	Firm
γ	Research efficiency	Firm
v	Vintage of capital	Firm

a constant rate over time, denoted g_v, and that there is a simple relationship between the age of the capital stock and the productivity of vintages given by $v(\text{age of capital}_i) = v_0(1+g_v)^{-\text{age of capital}_i}$, we estimate a regression of firm TFP on the age of the capital stock instrumented with the 5 year recent growth rate as in section 4. Similarly, we start from equation (5): $\log\left[\frac{\text{Emission}}{\text{Energy}}\right] = \log(\phi_s^e) - \epsilon_v \log v$ to estimate the elasticity of emissions to capital vintage ϵ_v using the same instrumental approach based on the 5 year recent growth rate.

At the firm level, we estimate the joint distribution of the firm-level variables v, γ and ξ by matching three firm-level moments: the ratio of intangibles over tangible assets, the age of the capital stock—using $v = (1+g_v)^{-\text{age of capital}_i}$—and the size of firms.

6.3 Calibration of Counterfactual Policies

We calibrate the four policy instruments—the carbon tax τ_e, the feebate (τ_e, τ_y), the subsidy to the newest vintage τ_V, and the intangible investments subsidy τ_a—in each country separately. While countries in practice are likely to consider a mix of carbon pricing and subsidies, we simulate one instrument at a time to isolate the properties of each policy. To ensure comparability across jurisdictions and instruments, we independently set each policy to generate the same 15% decline in each country's total corporate emissions. Appendix Figure A7 shows the resulting cross-country distribution of carbon taxes, and capital vintage and intangible investments subsidies.

While such a target may appear below the level of ambition needed to achieve the Paris Agreement goals of reducing emissions by 45% by 2030, we find that more ambitious targets are not always attainable in all countries for all instruments, especially when using subsidies. To avoid dropping too many countries from our sample, we choose a less ambitious target. This target may still be consistent with the goal of the Paris Agreement given that emissions as a ratio to GDP have been declining in the absence of policies and also because the model abstracts from other important margins of climate mitigation, including greening the electricity grid (energy utilities are excluded in the calibration) and the housing stock.

7 Quantitative Effects of Mitigation Policies

We now use the calibrated model to analyze the costs, efficacy and channels of different mitigation policies. We consider both carbon taxes and subsidies for capital upgrades and intangible investments. We also quantify how firms' endogenous decisions along key margins—capital upgrades and intangible investments—shape these costs.

7.1 Superiority of Carbon Taxes

The economic costs of carbon taxes are an order of magnitude smaller than those implied by subsidies calibrated to achieve the same reduction in emissions. While a carbon tax leads to a −0.3% decrease in the net present value of consumption (NPVC), subsidies for the newest capital vintage and for intangible investments both lead to declines of more than 4%, as shown in Table 6.[31,32] This result is consistent with the

[31]These changes in the NPVC account for both the new steady state consumption after the policy is implemented and the transition costs such as costs of investments. The change in the NPVC caused by a climate mitigation policy is a sufficient statistic for welfare comparison because we assume linear utility in aggregate consumption and all policies achieve equal emissions reductions. NPVC changes are GDP-weighted averages across countries in the sample. We abstract from climate damages due to GHG emissions because all policies induce the same reduction in emissions by 15%.

[32]Our estimate of the long-run impact of carbon taxes is consistent with studies such as Goulder and Hafstead (2017) who find a cost of about 1 percent of GDP and Finkelstein Shapiro and Metcalf (2023). See Metcalf and Stock (2020) for a review of empirical estimates.

notion that carbon taxes are the first-best mitigation tool.

Relative to subsidies, carbon taxes directly incentive firms to economize on emissions along all margins and in the most cost-efficient way. In contrast, subsidies are more narrow in scope: subsidies for the newest capital vintage only incentivize emissions reductions through vintage upgrades and capital accumulation and intangible investments subsidies through knowledge accumulation. As a result, subsidies distort the efficient allocation of inputs: subsidies for the newest capital vintage result in capital over-accumulation and excessive adoption of the newest vintage, while intangible investments subsidies lead to over-investment in intangible capital.[33] In general equilibrium, this increases the demand for labor—to produce capital goods in the case of subsidies for the newest vintage, and to invest in knowledge in the case of the intangible investments subsidies—pushing real wages up, and crowding out labor from the final good sectors. In addition, under the subsidy for the newest vintage, the capital goods sector expands to produce new capital goods, generating additional emissions which partially offsets the gains in the final goods sectors. Net present values of fiscal costs are also substantial: 5.7% of GDP for subsidies to the newest vintage and 12.9% for intangible investments subsidies. The higher fiscal costs of intangible investments subsidies stem from the fact that they need to be much more generous to achieve a 15% reduction in emissions, as shown in Figure A7.[34,35]

7.2 Importance of the Vintage Upgrade Margin

The ability of firms to upgrade vintages—one of the two new margins uncovered in section 4—lowers the costs of carbon taxes by an economically meaningful amount. To show this, we simulate the impact of a carbon tax that achieves the same 15% reduction in emissions but under the assumption that firms have to continue using the same vintage of capital they start with. As shown in Table 7, in this counterfactual, the tax leads to a drop in the NPVC by 0.42%, a 31% larger cost than in the case in which they

[33] While a well-calibrated intangible knowledge subsidy would make firms internalize the cross-firm knowledge externality, the size of a subsidy that delivers a 15% reduction in emissions is much larger than the optimal Pigouvian subsidy. We find in unreported simulations that smaller subsidies (around 5% for most countries) can increase output and consumption.

[34] For simplicity, we assume policies are financed with non-distortive lump-sum taxes and transfers. Incorporating distortions due to taxation would increase the economic costs of subsidies.

[35] The feebate has similar output and consumption cost as the carbon tax but its negative affects on firm profits are smaller, which may be considered an appealing feature.

Table 6: Effects of policies on aggregates

In Percentages	Carbon Tax	Carbon Feebate	New Vintage Subsidy	Intangible Subsidy
NPV of consumption	-.32	-.33	-4.54	-4.07
NPV of fiscal transfers	-.40	.05	5.70	12.94
Long-run consumption	-.36	-.36	2.82	-7.10
Long-run profits	-.50	-.03	2.77	-7.18
Long-run labor productivity	-.14	-.14	2.24	3.12
Long-run TFP	.03	.05	2.54	3.90
Share of firms updating	2.32	2.33	62.69	.00

Notes: Values denote percentage changes, relative to the actual economy, except for fiscal transfers (which are in share of GDP) and share of firms updating (which is in percent of total firms). NPV denotes net present value. A 4% time discount factor is used to compute the NPV of consumption. Output, consumption, profits, labor productivity, TFP refer to their value in the steady-state and are weighted averages across sectors within countries and across countries, where the weights are the country-specific sector shares and countries GDP. Fiscal transfers are the sum of the steady-state and transition net subsidies, annualized, and in percent of steady-state GDP in the counterfactual economy. All policies are calibrated to achieve a 15% reduction in emissions (in percentage change of the actual economy).

can upgrade (0.32%). When firms cannot upgrade, they mostly adjust to the tax by reducing their energy consumption.

Relatedly, allowing for the vintage upgrade margin significantly reduces the carbon tax required to achieve a 15% reduction in emissions. As shown in Table 7, the average carbon tax is \$36.1 – \$29.1 = \$7 (or 20%) lower once one takes into account this new margin. Results are quantitatively similar when we consider a carbon feebate instead of a carbon tax.

This reduction in the cost and necessary size of carbon taxes is driven entirely by decisions by the firms furthest away from the capital vintage frontier to upgrade to the best available vintage. Firms' decisions to upgrade depend on the distance to the frontier vintage. Only firms furthest from the frontier choose to upgrade. Upgrades by a small share of firms can therefore significantly reduce aggregate emission intensities. Moreover, consistent with our empirical findings, in our calibrated model laggards tend to be large. When laggard firms are large, their upgrade decisions are even more important. Indeed, although only 2.3% of firms choose to upgrade when allowed to do so, this leads to a 31% difference in the economic cost of the carbon tax. It is therefore important that our calibrated model matches the full distribution of firm-level heterogeneity.

Even more so than for the carbon tax, the costs that result from subsidies for the newest capital vintage are substantially lower once firms are allowed to upgrade their vintages. In the counterfactual in which firms are not allowed to upgrade their vintage, subsidies lead to a drop in the NPVC by 21.9%, which is an order of magnitude larger than the 4.5% decline when firms are allowed to upgrade (Table 7). When firms cannot upgrade, those that were already using the best vintage accumulate more capital. In partial equilibrium, firms using an older vintage do not react. In general equilibrium, however, they lose market share to firms that use the newest vintage. But when firms are allowed to upgrade, 63% of them respond to the policy by upgrading. This means that such subsidies considerably leverage the vintage upgrade margin. As a result, the difference in economic costs of subsidies to the newest capital vintage relative to carbon taxes becomes significantly smaller once accounting for this margin (4.22 vs 21.51 p.p.).

The initial distribution of vintages also shapes how many firms upgrade in response to subsidies for the newest vintage. In our simulations, countries with older capital stocks see fewer firms upgrading and smaller reductions in the costs of subsidies from the capital upgrade margin (Appendix Figure A11). Intuitively, if a country has many firms with old capital stocks, fewer firms need to update in equilibrium to generate a 15% reduction in emissions. As a result, the impact of shutting this margin down varies significantly across countries.

Overall, these results highlight the importance of specifying technologies that are tightly connected to empirical evidence, incorporating all the margins firms use to respond to policies. Our model allows for new margins, which are crucial as shown by the significantly lower costs of policies when firms are able to upgrade vintages. Finkelstein Shapiro and Metcalf (2023) also show that technological adoption lowers the costs of policies. While they find that a carbon tax can lead to increases in consumption, our results suggest that carbon taxes still decrease consumption in the short and long run.[36] A key difference is that in our model firms can adjust through additional margins whose relevance is supported by our empirical results, for example, by reducing energy consumption and investing in intangibles.

[36] In their model, firms can freely enter and exit and have a choice between a green and dirty technology.

Table 7: Counterfactuals with and without vintage upgrade margins

In Percentages	Carbon Tax		New Vintage Subsidy	
	Upgrade	No Upgrade	Upgrade	No Upgrade
Change in NPVC (Average)	-.38	-.49	-4.87	-23.35
Change in NPVC (IQR)	[-.58, -.13]	[-.94,-.25]	[-4.13, -.05]	[-20.75,-8.06]
Level of Tax/Subsidy (Average)	29.09	36.10	19.91	69.53
Level of Tax/Subsidy (IQR)	[23.65,38.25]	[36.87,50.31]	[8.01,13.66]	[54.52,75.33]

Notes: NPVC denotes net present value of consumption. Change in NPVC is in percentage change of the actual economy. A 4% time discount factor is used to compute the NPV of consumption. Averages are weighted by the country-specific sector shares and by countries GDP. Carbon tax is expressed in dollars. Subsidy is expressed in percentages. All policies are calibrated to achieve a 15% reduction in emissions (in percentage change of the actual economy).

7.3 Subsidies and Intertemporal Trade-Offs

Unlike carbon taxes and intangible investments subsidies, subsidies for the newest vintage generate consumption gains in the long run, as can be seen in the 2.5% increase in TFP and 2.8% increase in consumption (Table 6). This is because, consistent with our firm-level empirical analysis, capital upgrades are green biased: newer capital vintages both raise productivity—lowering energy use per unit of output—and lead to lower emissions conditional on energy usage. Accordingly, our model allows capital vintages to enter both the emission (Equation 5) and the output (Equation 4) production functions. Note that the positive effect of newest vintage subsidies on productivity is partially mitigated by the misallocation of inputs induced by the subsidy, which lowers long-run consumption, as discussed earlier.

These long-run gains implied by subsidies to the newest vintage are even more striking when compared to the effects of mitigation policies that target Hicks-neutral productivity improvements without a green bias. To show this, we look at the costs of subsidies in intangible investments, which boost intangible knowledge and raise the productivity of all factors but without a green bias. As shown in Table 6, this policy leads to large consumption losses in the long-run (-7.1%). While raising productivity lowers emissions per unit of output, it also increases production and thus energy demand. Therefore, as long as the supply of energy is somewhat elastic, in general equilibrium intangible investments subsidies lead to emission reductions only through pushing an inefficiently large fraction of workers to become scientists, thus decreasing output. An important caveat is that we abstract from “green” research, such as research in renewable energy, electrification, or emission-saving machines.[37]

Subsidies for the newest capital vintage also generate larger short-term costs than other mitigation policies. This is because many firms upgrade and invest in newer capital vintages, which takes resources away from consumption. This distribution of costs and gains contrasts with much flatter time-profiles for both carbon taxes and intangible investments subsidies.

The combination of short-run costs and long-term gains generates an intertemporal trade-off. A social planner that is sufficiently more patient than private sector agents would put relatively more weight on future periods and may therefore find subsidies for the newest capital vintage as appealing as carbon taxes. The lower the social discount rate, the more appealing these subsidies become (Figure A9). Under a fixed market rate of 4%, the social discount rate required to make subsidies to the newest vintage as appealing as carbon taxes is around 1.5%, with an interquartile range across countries of 1.3-4.0%. This is within the range of discount rates considered in the climate change literature. Lower social discount rates can be justified on various grounds, including myopic behavior by firms due to financial constraints, or ethical concerns regarding future generations, such as a moral requirement that consumption levels of future generations do not decrease (Ramsey, 1928; Acemoglu et al., 2012; Campbell and Martin, 2021).

7.4 Country Heterogeneity

Differences in industry composition and in the mix of technologies used in each industry lead to significant variation across countries in the required carbon tax and subsidies to achieve a 15% emission cut and in the estimated costs across mitigation policies. It is therefore important to account for empirical industry and firm-level patterns within each country to calibrate and evaluate mitigation policies.

Accounting for country-specific firm-level heterogeneity is critical to design and

[37] In our model, intangible investments can capture any productivity-enhancing investments that decrease emissions only through lowering energy consumption per unit of output, e.g., better management practices. This simplification implies that our model cannot be used to assess the effectiveness of subsidies directing research towards lowering emissions. While such subsidies can be important role to play (Acemoglu et al., 2012), the share of "green" R&D remains small: for instance, Hasna et al. (2023) document that under 7% of patents in the last fifteen years have been for low-carbon technologies, while Touboul et al. (2023) study data from European Patent Office in 2018 and report 5% of patents are linked to climate mitigation and 0.6% to adaptation.

quantify the costs of carbon taxes. In our sample of 23 countries, we find that the increase in the carbon tax required to decrease emissions by 15% ranges from less than $10 to $60 a ton, with an interquartile range (IQR) of $23.65 to $38.25 (see Table 7). The dispersion in the NPVC costs is also large, with an IQR of -.6% to -.1%. The importance of the capital upgrade margin also varies across economies. Vintage upgrades are more important in countries where industries and the mix of technologies are more energy intensive, as firms find upgrades more appealing. In such countries, more firms adopt newer vintages following the carbon tax which in turn leads to larger reductions in the cost of the tax (see Appendix Figure A10).

Taking into account country characteristics is particularly important for evaluating tradeoffs associated with subsidies. Indeed, the NPVC cost of subsidies, their long-run gains, and the importance of the capital upgrade margin vary with an economy's technologies and its initial distribution of capital vintages. Table 7 shows wide cross-country dispersion in NPVC costs, with an interquartile range of -4.13% to -.05%. These differences in long-run gains are related to technological characteristics. For instance, we find a strong association between the extent of long-run gains and the (average) capital intensity of production (κ) in the cross-section of countries (Appendix Figure A8). In addition, and as shown in Appendix Figure A11, countries that start from older capital stocks need fewer firms to upgrade to achieve a 15% reduction in emissions. This in turn implies lower transition costs, and larger long-run gains.

8 Conclusions

This paper shows that technological factors play an important role in explaining why many large listed firms remain well behind the current frontier of environmental performance—across countries and sectors. Wider adoption of technologies embedded in newer vintages of physical capital and intangible investments that lift productivity could help close these gaps. Crucially, capital embedded technologies are green biased, reducing emissions beyond lowering energy consumption.

We propose a multi-sector heterogeneous-firm general equilibrium model that incorporates two key margins of adjustment—upgrades to newer vintages of capital and intangible investments—that is tightly linked with this empirical evidence. Counterfactual simulations of the calibrated model help better evaluate policy options to mitigate climate change.

Accounting for firms' endogenous technological choices is important because climate laggards matter for total emissions. Carbon pricing can push firms furthest away from the frontier to choose to upgrade to newer vintages. Accounting for this impact is important—even when only a few firms upgrade, the macroeconomic cost of carbon taxes can be significantly smaller. Subsidies for investments in newer capital-embedded technologies are costly, but present an intertemporal tradeoff that must be evaluated by accounting for a range of country-specific factors.

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A1 Annex: Model Appendix

A1.1 Market Clearing Conditions

In each country, the markets for all final goods i in all sectors s clear.

$$\forall\ s = 1, ..., S, \quad \forall\, i \in \mathscr{S}_s, \quad c_{si} = y_{si} \tag{20}$$

Denoting $x_{i\,v_s}$ the demand of capital goods of vintage v_s by firm i and ℓ_{v_s} the labor used in the production of capital goods of this vintage, the market clearing condition for capital goods of vintage v_s is given by

$$\forall\ v_s = 1, ..V_s \quad \sum_{i \in \mathscr{S}_s} x_{i\,v_s} = z_{v_s} \ell_{v_s}. \tag{21}$$

The bonds market clears $B_t = 0$ as well as the labor market.

$$\sum_{s=1}^{S} \sum_{i \in \mathscr{S}_s} \left(\ell^a_{si} + \ell_{si}\right) + \sum_{s=1}^{S} \sum_{v_s \in \mathscr{V}_s} \ell_{v_s} = L \tag{22}$$

A1.2 Equilibrium Definition

An equilibrium is a set of value functions $\mathscr{U}, \mathscr{V}_s(a, k, v, \gamma, \xi)$, and policy rules $p_s(a, k, v, \gamma, \xi), k'_s(a, k, v, \gamma, \xi), a'_s(a, k, v, \gamma, \xi), \ell_s(a, k, v, \gamma, \xi), n_s(a, k, v, \gamma, \xi)$, a mass function $M_s(a, k, v, \gamma, \xi)$, a set of capital good prices $\{q_{v_s}\}_{v_S=1}^{V_s}$ for each sector $s = 1...S$, and a wage w such that

1. Taking final goods prices, wages, net transfers T and aggregate profits Π as given, households maximize their utility.
2. Given the wage and the capital goods prices, the firm's policy rules and the value function solves the problem (9).
3. Given the wage and the capital goods prices, capital goods firms maximize their profits (14).
4. The mass function $M_s(a, k, v, \gamma, \xi)$ is consistent with the entry condition (12), the exit condition (13), and the policy rules of the final good firms.
5. The final goods (20), bonds, capital goods (21), and labor markets clear (22).

A1.3 Model Solution

In this section, we solve the model and present the main equations of interest, including the optimal variable input choices, pricing, and dynamic decisions (capital, vintage, and R&D).

Firm's choice of variable inputs We first analyze how the firm optimally chooses labor and energy consumption. The operating costs function of the firm is given by:

$$C(\ell, n) = w\ell + mn + \tau_e n v^{-\epsilon_v} \tag{23}$$

Dropping the industry and firm subscript, and denoting μ the lagrange multiplier associated with the production technology in the cost-minimization problem, the first order conditions with respect to ℓ and n are given by:

$$\lambda_s \frac{\mu y}{\ell} = w \tag{24}$$

$$\eta_s \frac{\mu y}{n} = m + \tau_e \frac{e}{n} \tag{25}$$

Combining the two gives:

$$\frac{\eta_s}{\lambda_s} \ell = \frac{m + \tau_e v^{-\epsilon_v}}{w} n$$

Substituting back into the production function, one gets:

$$y = A_s^{\rho} a (\ell)^{\lambda_s + \eta_s} \left(\frac{\eta_s}{\lambda_s} \frac{w}{m + \tau_e v^{-\epsilon_v}} \right)^{\eta_s} (v k_v)^{\kappa_s}$$

We then obtain ℓ and n:

$$\ell = \Gamma^{\ell}_{sv} y^{\frac{1}{\eta_s+\lambda_s}}$$

$$\Gamma^{\ell}_{sv} = A_s^{-\frac{\rho}{\eta_s+\lambda_s}} a^{-\frac{1}{\lambda_s+\eta_s}} \left(\frac{\lambda_s}{\eta_s}\frac{m+\tau_e v^{-\epsilon_v}}{w}\right)^{\frac{\eta_s}{\eta_s+\lambda_s}} (v k_v)^{-\frac{\kappa_s}{\eta_s+\lambda_s}}$$

$$n = \Gamma^{n}_{sv} y^{\frac{1}{\eta_s+\lambda_s}}$$

$$\Gamma^{n}_{sv} = A_s^{-\frac{\rho}{\eta_s+\lambda_s}} a^{-\frac{1}{\lambda_s+\eta_s}} \left(\frac{\eta_s}{\lambda_s}\frac{w}{m+\tau_e v^{-\epsilon_v}}\right)^{\frac{\lambda_s}{\eta_s+\lambda_s}} (v k_v)^{-\frac{\kappa_s}{\eta_s+\lambda_s}}$$

For future reference, we denote

$$\tilde{\Gamma}^{\ell}_{sv} = A_s^{-\frac{\rho}{\eta_s+\lambda_s}} \left(\frac{\lambda_s}{\eta_s}\frac{m+\tau_e v^{-\epsilon_v}}{w}\right)^{\frac{\eta_s}{\eta_s+\lambda_s}} v^{-\frac{\kappa_s}{\eta_s+\lambda_s}}$$

so that $\Gamma^{\ell}_{sv} = \tilde{\Gamma}^{\ell}_{sv}(a k_v^{\kappa_v})^{-\frac{1}{\lambda_s+\eta_s}}$

From the definition of operating costs given by equation (23), we have

$$C(\ell, n) = w\ell\left(1+\frac{\eta_s}{\lambda_s}\right) = \Gamma_{sv} y^{\frac{1}{\eta_s+\lambda_s}} \tag{26}$$

$$\Gamma_{sv} = \Gamma^{\ell}_{sv}\left(w\left(1+\frac{\eta_s}{\lambda_s}\right)\right) \tag{27}$$

For future reference we denote,

$$\tilde{\Gamma}_{sv} = \tilde{\Gamma}^{\ell}_{sv}\left(w\left(1+\frac{\eta_s}{\lambda_s}\right)\right) \tag{28}$$

so that $\Gamma_{sv} = \tilde{\Gamma}_{sv}(a k_v^{\kappa_v})^{-\frac{1}{\lambda_s+\eta_s}}$.

We can then rewrite operating profits as

$$p_{si}^{1-\sigma}\xi_s P_s^{\sigma} Y_s(1+\tau_y) - \Gamma_{sv}\left(p_{si}^{-\sigma}\xi_s P_s^{\sigma} Y_s\right)^{\frac{1}{\eta_s+\lambda_s}}$$

The first order condition for the optimal price is then given by:

$$(\sigma-1)p_{si}^{-\sigma}\xi_s P_s^{\sigma} Y_s(1+\tau_y) = \Gamma_{sv}\frac{\sigma}{\eta_s+\lambda_s}p_{si}^{-\frac{\sigma}{\eta_s+\lambda_s}-1}\left(\xi_s P_s^{\sigma} Y_s\right)^{\frac{1}{\eta_s+\lambda_s}} \tag{29}$$

$$p_{si}^{1-\sigma+\frac{\sigma}{\eta_s+\lambda_s}} = \frac{\Gamma_{sv}}{(1+\tau_y)}\frac{\sigma}{(\sigma-1)(\eta_s+\lambda_s)}\left(\xi_s P_s^{\sigma} Y_s\right)^{\frac{1}{\eta_s+\lambda_s}-1} \tag{30}$$

$$p_{si} = \frac{\sigma}{\sigma-1}\frac{\Gamma_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}y_{si}^{\frac{1}{\eta_s+\lambda_s}-1} \tag{31}$$

We can rewrite this as a constant markup over marginal cost:

$$p_{si} = \frac{\sigma}{\sigma-1}MC_{si}$$
$$MC_{si} = \frac{\Gamma_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}y_{si}^{\frac{1}{\eta_s+\lambda_s}-1}$$

We now solve for the equilibrium size (output) of a firm:

$$\left(\frac{y_{si}}{\xi_{si}Y_s}\right)^{-\frac{1}{\sigma}}P_s = \frac{\sigma}{\sigma-1}\frac{\Gamma_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}y_{si}^{\frac{1}{\eta_s+\lambda_s}-1}$$

$$\begin{aligned}
y_{si} &= \left[\left(\frac{\sigma}{\sigma-1}\frac{\Gamma_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}\frac{1}{P_s}\right)(\xi_{si}Y_s)^{-\frac{1}{\sigma}}\right]^{\frac{1}{1-\frac{1}{\eta_s+\lambda_s}-\frac{1}{\sigma}}} \\
&= \left[\left(\frac{\sigma}{\sigma-1}\frac{\Gamma_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}\frac{1}{P_s}\right)^{-1}(\xi_{si}Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma(\eta_s+\lambda_s)}{\sigma+\eta_s+\lambda_s-\sigma(\eta_s+\lambda_s)}} \\
&= \left[\left(\frac{\sigma}{\sigma-1}\frac{\tilde{\Gamma}_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}\frac{1}{P_s}\right)^{-1}(\xi_{si}Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma(\eta_s+\lambda_s)}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}(k_v^{\kappa_s}a)^{\frac{\sigma}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}} \\
&= \left[\frac{\sigma-1}{\sigma}(1+\tau_y)(\lambda_s+\eta_s)P_s(\xi_{si}Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma(\eta_s+\lambda_s)}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}\tilde{\Gamma}_{sv}^{-\frac{\sigma(\eta_s+\lambda_s)}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}(k_v^{\kappa_s}a)^{\frac{\sigma}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}
\end{aligned}$$

In addition, the size of a firm in value is given by

$$p_{si}y_{si} = \frac{\sigma}{\sigma-1}\frac{\Gamma_{sv}}{(1+\tau_y)(\eta_s+\lambda_s)}y_{si}^{\frac{1}{\eta_s+\lambda_s}}$$

Substituting the expression for y_{si} just found into the expressions for ℓ and n, the implied optimal level of labor and energy are given by

$$\ell = \Lambda_{s\xi} A_s^{\hat{\rho}} \left(\frac{\lambda_s}{w}\right)^{\hat{\lambda}_s+1} \left(\frac{\eta_s}{m+\tau_e v^{-\epsilon_v}}\right)^{\hat{\eta}_s} (vk_v)^{\hat{\kappa}_s}$$
$$n = \Lambda_{s\xi} A_s^{\hat{\rho}} \left(\frac{\lambda_s}{w}\right)^{\hat{\lambda}_s} \left(\frac{\eta_s}{m+\tau_e v^{-\epsilon_v}}\right)^{\hat{\eta}_s+1} (vk_v)^{\hat{\kappa}_s}$$
$$\Lambda_{s\xi} = \left[\frac{\sigma-1}{\sigma}(1+\tau_y)P_s(\xi_{si}Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}$$

Optimal Capital and Research Intensity Operating profits are given by

$$\pi_{si}+\kappa_s = py(1+\tau_y) - \Gamma_{sv} y^{\frac{1}{\eta_s+\lambda_s}} \tag{32}$$
$$= py(1+\tau_y)\left(1-\frac{\sigma-1}{\sigma}(\lambda_s+\eta_s)\right) \tag{33}$$
$$= \left(\frac{\sigma}{\sigma-1}\frac{1}{(\eta_s+\lambda_s)}-1\right)\Gamma_{sv} y_{si}^{\frac{1}{\eta_s+\lambda_s}} \tag{34}$$
$$= \Omega_{sv\xi}(ak_v^{\kappa_s})^{-\frac{1}{\eta_s+\lambda_s}+\frac{1}{\lambda_s+\eta_s}\frac{\sigma}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}} \tag{35}$$
$$= \Omega_{sv\xi}(ak_v^{\kappa_s})^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} \tag{36}$$
$$= \Omega_{sv\xi} k_v^{\hat{\kappa}_s} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} \tag{37}$$

with

$$\Omega_{sv\xi} = \left[\frac{\sigma-1}{\sigma}(1+\tau_y)(\lambda_s+\eta_s)P_s(\xi_{si}Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}} \left(\frac{\sigma}{\sigma-1}\frac{1}{(\eta_s+\lambda_s)}-1\right)\tilde{\Gamma}_{sv}^{\frac{(1-\sigma)(\eta_s+\lambda_s)}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}$$

We assume $\frac{\sigma}{\sigma-1} > \eta_s+\lambda_s$.

We now go back to our profit function:

$$v(a,k,v,\gamma,\xi) = \max_{\ell_a,x,v',a',k'_v}\left\{\Omega_{sv\xi} k_v^{\hat{\kappa}_s} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} - \sum_w q_w x_w - w(1-\tau_a)\ell_a + \frac{1}{1+r} v(a',k'_{v'},v',\gamma,\xi)\right\} \tag{38}$$

$$k'_{v'} = (1-\delta_k)k_{v'} + x_{v'} \tag{39}$$
$$a' = (1-\delta_a)a + \left(\frac{\ell_a}{\gamma}\right)^{\alpha_s} \tag{40}$$

If μ_k, μ_a denote the Lagrange multipliers associated with the law of motion of capital and knowledge respectively, the FOCs and the E.C. are given by:

$$
\begin{aligned}
q_v &= \mu_k && (41)\\
w(1-\tau_a) &= \mu_a \alpha \ell_a^{\alpha-1}\gamma^{-\alpha} && (42)\\
\frac{1}{1+r} v_k(a', k_v', v, \gamma) &= \mu_k && (43)\\
\frac{1}{1+r} v_a(a', k_v', v, \gamma) &= \mu_a && (44)\\
v_k(a,k,v,\gamma) &= \Omega_{sv\xi}\hat{\kappa}_s k_v^{\hat{\kappa}_s-1} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} + \mu_k(1-\delta_k) && (45)\\
v_a(a,k,v,\gamma) &= \Omega_{sv\xi}\hat{\kappa}_s k_v^{\hat{\kappa}_s} \frac{a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}-1}}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)} + \mu_a(1-\delta_a). && (46)
\end{aligned}
$$

This results in the following condition:

$$
\begin{aligned}
\Omega_{sv\xi}\hat{\kappa}_s k_v^{\hat{\kappa}_s-1} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} + q_v(1-\delta_k) = (1+r)q_v && (47)\\
k_v = \left(\frac{\Omega_{sv\xi}\hat{\kappa}_s a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}}}{q_v(r+\delta_k)}\right)^{\frac{1}{1-\hat{\kappa}_s}} && (48)\\
\Omega_{sv\xi}\hat{\alpha}_s \frac{k_v^{\hat{\kappa}_s}\ell_a^{\hat{\alpha}_s-1}}{\gamma^{\hat{\alpha}_s}\hat{\delta}_a} + w(1-\tau_a)(1-\delta_a) = (1+r)w(1-\tau_a) && (49)\\
\ell_a = \left(\frac{\Omega_{sv\xi}\hat{\alpha}_s k^{\hat{\kappa}_s}}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right)^{\frac{1}{1-\hat{\alpha}_s}} && (50)
\end{aligned}
$$

where we denote $\hat{\delta_a} = \delta_a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta+\lambda)}-1}$, and where we used the steady-state expression of knowledge $a = \left(\frac{\ell_a}{\gamma}\right)^{\alpha}\frac{1}{\delta_a}$.

We can compute ℓ_a as a function of k_v by taking the ratio between the first and third equations above:

$$
\frac{\hat{\kappa}_s}{\hat{\alpha}_s}\frac{\ell_a}{k_v\delta_a} = \frac{(r+\delta_k)q_v}{(r+\delta_a)w(1-\tau_a)} \iff w\ell_a = \frac{(r+\delta_k)\delta_a q_v k_v}{(r+\delta_a)(1-\tau_a)}\frac{\alpha_s}{\kappa_s} \tag{51}
$$

Equating equation (51) with the previous one gives:

$$k_v = \left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a q_v}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \left[\frac{\Omega_{sv\xi}\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \tag{52}$$

Vintage decision. The last margin of adjustment to policies is the possibility for firms to upgrade to a better vintage of capital. This decision amounts to comparing the value of upgrading to the value of continuing production with the older vintage. Using the optimality condition for capital (15), the steady-state value of an incumbent (9) that keeps its old vintage is given by

$$\begin{aligned}
v(a,k,v,\gamma,\xi) &= \frac{1}{r(1+r)}\Omega_{sv\xi}k_v^{\hat{\kappa}_s}a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} - \frac{1}{r}q_v\delta_k k_v - \frac{1}{r}w(1-\tau_a)\ell_a \\
&= \frac{1}{r(1+r)}\frac{q_v(r+\delta_k)}{\hat{\kappa}_s}k_v - \frac{1}{r}q_v\delta_k k_v - \frac{1}{r}\frac{(r+\delta_k)\delta_a q_v k_v}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s} \\
&= \frac{1}{r}q_v\left(\frac{1}{1+r}\frac{(r+\delta_k)}{\hat{\kappa}_s} - \delta_k - \frac{(r+\delta_k)\delta_a}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s}\right)k_v \\
&= \frac{1}{r}q_v^{\frac{-\hat{\kappa}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left(\frac{1}{1+r}\frac{(r+\delta_k)}{\hat{\kappa}_s} - \delta_k - \frac{(r+\delta_k)\delta_a}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s}\right) \\
&\qquad \times \left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \left[\frac{\Omega_s(v,\gamma,\xi,\tau_e)\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}}
\end{aligned} \tag{53}$$

where the second line uses equation (47). Alternatively, a firm could decide to upgrade its vintage of capital, v_{si}. Let's assume for the moment that firms upgrade to the best available vintage, V_s, and recall that, motivated by empirical evidence, firms that upgrade retire the vintage of capital that they had been using so far and recover only a fraction of its value. The value of upgrading is then given by

$$\begin{aligned}
v^{up}(a,k_v,v,\gamma,\xi) &= q_V^{\frac{-\hat{\kappa}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{1}{r}\left(\frac{1}{1+r}\frac{(r+\delta_k)}{\hat{\kappa}_s} - \delta_k - \frac{(r+\delta_k)\delta_a}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s}\right) - 1\right] \\
&\times \left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \left[\frac{\Omega_s(v,\gamma,\xi,\tau_e)\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}} + \chi q_v k_v(1-\delta_k)
\end{aligned} \tag{54}$$

A firm upgrade if and only if the value (54) exceeds the value $v(a,k,v,\gamma,\xi)$.

We now show that the following lemma

Lemma 2 (Vintage decision)**.** *Assume that the elasticity of z_v to v is strictly higher than* -1.

1. *If a firm updates its vintage, it upgrades to the best vintage V_s.*
2. *There exists a unique $\underline{v}_s$ such that firm upgrade to V_s if and only if $v_s < \underline{v}_s$.*

A sufficient condition for the first bullet point is that the last value function is increasing in v. After simplification of the profit function, one finds that the first component of the value function $q_V^{\frac{-\hat{\kappa}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{1}{r}\left(\frac{1}{1+r}\frac{(r+\delta_k)}{\hat{\kappa}_s}-\delta_k-\frac{(r+\delta_k)\delta_a}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s}\right)-1\right]\left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{\Omega_{sV\xi}\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{}{1-\hat{\kappa}}}$ is proportional to $\left(\frac{v}{q_v}\right)^{-\frac{\hat{\kappa}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}$. Since $\hat{\kappa} > 0$ by assumption, a sufficient condition for the value function to be increasing in v is that $\frac{v}{q_v}$ increases in v. This in turn is true when when the elasticity of z_v to v is strictly higher than -1.

A sufficient condition for the second bullet point is that the difference between the value function in case of upgrading and not upgrading be decreasing in v:

$$
\begin{aligned}
& q_V^{\frac{-\hat{\kappa}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{1}{r}\left(\frac{1}{1+r}\frac{(r+\delta_k)}{\hat{\kappa}_s}-\delta_k-\frac{(r+\delta_k)\delta_a}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s}\right)-1\right] \\
&\qquad\qquad \times\left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{\Omega_{sV\xi}\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \\
& -q_v^{\frac{-\hat{\kappa}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{1}{r}\left(\frac{1}{1+r}\frac{(r+\delta_k)}{\hat{\kappa}_s}-\delta_k-\frac{(r+\delta_k)\delta_a}{(r+\delta_a)}\frac{\alpha_s}{\kappa_s}\right)-\chi(1-\delta_k)\right] \\
&\qquad\qquad \times\left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}}\left[\frac{\Omega_{sv\xi}\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}}
\end{aligned}
$$

The first term is independent of the current vintage of the firm, v. By the same reasoning as before, the second term is strictly increasing in v under the assumption that v/q_v is strictly increasing in v. Therefore if this condition is satisfied, the difference is strictly decreasing in v. In addition, note that the decision to upgrade is independent of γ and ξ.

A1.3.1 Consistency with Stylized Facts.

Energy intensity is decreasing with vintage and research efficiency (conditional on asset/size):

$$\begin{aligned}
\frac{n}{y} &= \frac{1}{m+\tau_e v^{-\epsilon_v}} \frac{\eta_s}{\eta_s+\lambda_s} \frac{C}{y} = \frac{1}{m+\tau_e v^{-\epsilon_v}} \frac{\eta_s}{\eta_s+\lambda_s} \Gamma_{sv} y_{si}^{\frac{1}{\eta_s+\lambda_s}-1} \\
&= \frac{1}{m+\tau_e v^{-\epsilon_v}} \frac{\eta_s}{\eta_s+\lambda_s} \left(\frac{\Omega_{sv\xi}}{\frac{\sigma}{\sigma-1}\frac{1}{\lambda_s+\eta_s}-1} \right)^{1-\eta_s-\lambda_s} \Gamma_{sv}^{\eta_s+\lambda_s} (a k_v^{\kappa_s})^{1-\frac{1}{\sigma+(1-\sigma)(\lambda+\eta)}} \\
&= \frac{1}{m+\tau_e v^{-\epsilon_v}} \frac{\eta_s}{\eta_s+\lambda_s} \left(\frac{\Omega_{sv\xi}}{\frac{\sigma}{\sigma-1}\frac{1}{\lambda_s+\eta_s}-1} \right)^{1-\eta_s-\lambda_s} \tilde{\Gamma}_{sv}^{\eta_s+\lambda_s} (a k_v^{\kappa_s})^{-\frac{1}{\sigma+(1-\sigma)(\lambda+\eta)}} \\
&= \frac{1}{m+\tau_e v^{-\epsilon_v}} \frac{\eta_s}{\eta_s+\lambda_s} \left(\frac{\Omega_{sv\xi}}{\frac{\sigma}{\sigma-1}\frac{1}{\lambda_s+\eta_s}-1} \right)^{1-\eta_s-\lambda_s} \tilde{\Gamma}_{sv}^{\eta_s+\lambda_s} (k_v^{\alpha_s+\kappa_s})^{-\frac{1}{\sigma+(1-\sigma)(\lambda+\eta)}} \\
&\qquad \times \left(\frac{(r+\delta_k)}{(r+\delta_a)\gamma\delta_a^{\frac{1}{\alpha_s-1}}} \frac{\alpha_s}{w\kappa_s} q_v \right)^{-\frac{\alpha_s}{\sigma+(1-\sigma)(\lambda+\eta)}}
\end{aligned}$$

where we have used the optimal share of intangibles over tangibles given by

$$\frac{a^{\frac{1}{\alpha_s}}}{q_v k_v} = \frac{\ell_a}{\gamma \delta_a^{\frac{1}{\alpha_s}} q_v k_v} = \frac{(r+\delta_k)}{(r+\delta_a)\gamma\delta_a^{\frac{1}{\alpha_s-1}}} \frac{\alpha_s}{w\kappa_s} \tag{55}$$

and the expression for operating costs given by $C = \Gamma_{sv\xi} y_{si}^{\frac{1}{\eta_s+\lambda_s}}$.

Finally, note that we used equation (37) to find an expression for y as a function of k and a, and we used equation (55) to find an expression of a as a function of k_v. We also assumed that $\tau_a = 0$.

Hence we have

$$\ln \frac{n}{y} = \ln c_s - \zeta_{v1} \ln v + \zeta_{v2} \ln(m + \tau_e v^{-\epsilon_v}) + \zeta_\gamma \ln \gamma - \zeta_k \ln k + \zeta_\xi \ln \xi_{si}$$

$$\text{with} \quad \zeta_{v1} = \frac{\kappa_s + \alpha_s \epsilon_{qv}}{\sigma + (1-\sigma)(\eta_s + \lambda_s)}$$

$$\zeta_{v2} = \frac{\eta_s}{\sigma + (1-\sigma)(\eta_s + \lambda_s)} - 1$$

$$\zeta_\gamma = \frac{\alpha_s}{\sigma + (1-\sigma)(\eta_s + \lambda_s)}$$

$$\zeta_\xi = \frac{1 - \eta_s - \lambda_s}{\sigma + (1-\sigma)(\eta_s + \lambda_s)}$$

$$\zeta_k = \frac{\alpha_s + \kappa_s}{\sigma + (1-\sigma)(\lambda_s + \eta_s)}$$

and $\ln c_{st}$ is a time and sector-specific variable. By assumption:

$$\ln \frac{e}{n} = -\epsilon_v \ln v$$

Combining both equations give the first result of the proposition.

For TFP, we use the production function, the optimal pricing decision and the expression for the operating cost (26) and (27), and recalling that our measure of TFP is estimated from revenues following Asker et al. (2014), and we obtain:

$$py = \text{TFP} \times \text{C}^{\left(1-\frac{1}{\sigma}\right)(\lambda_s+\eta_s)} \times k_v^{\kappa_s\left(1-\frac{1}{\sigma}\right)}$$

$$\ln \text{TFP} = \left(1 - \frac{1}{\sigma}\right) \left[\ln a + \kappa_s \ln v_i + \rho \ln A_s\right] + \frac{1}{\sigma} \log \xi_i + \ln P_s + \frac{1}{\sigma} \ln Y_s$$
$$+ \left(1 - \frac{1}{\sigma}\right) \left[\lambda_s \ln\left(\frac{\lambda_s}{\lambda_s + \eta_s}\right) + \eta_s \ln\left(\frac{\eta_s}{\lambda_s + \eta_s}\right) - \eta_s \ln\left(m + \tau_e v^{-\epsilon_v}\right) - \lambda_s \ln w\right]$$

where C is the variable cost. We then use equation (55) to substitute for a and we get:

$$\ln \mathrm{TFP} = \left(1-\frac{1}{\sigma}\right)\alpha_s \ln\left(\frac{1}{\gamma}\right) + \left(1-\frac{1}{\sigma}\right)\alpha_s \ln k + \left(1-\frac{1}{\sigma}\right)\kappa_s \ln v_i + \frac{1}{\sigma}\log \xi_i$$
$$- \left(1-\frac{1}{\sigma}\right)\eta_s \ln\left(m + \tau_e v^{-\epsilon_v}\right) + \ln z_{st}$$

where $\ln z_{st}$ which is common to all firms in a time, country and sector specific variable which is common to all firms. This shows that firms with newer vintages and higher knowledge intensity also have higher TFP.

A2 Annex: Estimation

A2.1 Internal Calibration of non firm-specific parameters

A sector correspond to a 2-digit SIC industry to allow for enough firms in each sector for us to target firm-level moments. We explain below which moments we target and which moment is most informative for each parameter.

Consistent with the households' optimality condition (2), we calibrate the elasticity of utility to the consumption in each sector, β_s, to match the share of sales of each sector separately for each country: $\beta_s = \frac{\sum_{i\in\Omega_s} p_i y_i}{\sum_s \sum_{i\in\Omega_s} p_i y_i}$. To ensure that our model is consistent with the overall empirical distribution of economic activities, we reweight our shares to match coarser sectoral shares.[38]

The elasticity of output to capital κ_s is identified using the average mark-up, following the following formula: Sales $= \frac{\sigma}{\sigma-1}\frac{\text{COGS}}{\eta_s+\lambda_s}$, where COGS stands for "cost of goods sold". Using the assumption of constant returns to scale, $\kappa_s = 1-\lambda_s-\eta_s-\alpha_s$, and the average sales and cost of goods sold, from our dataset, we start with estimating $\kappa_s+\alpha_s$ as follows: $\kappa_s+\alpha_s = 1-\frac{\sigma}{\sigma-1}\frac{\sum_{i\in\Omega_s}\text{COGS}_i}{\sum_{i\in\Omega_s}\text{Sales}_i}$ where σ is externally calibrated. This captures the share of income going to the owners of the firm, of the stock of physical capital and of the intangible capital. The elasticities of output to labor and energy (λ_s, η_s) are estimated using the first order conditions of the firm, which imply that they are related to the share of costs going to each factor. Using our previous estimate of $(\kappa_s+\alpha_s)$ we obtain each parameter from the following expressions

$$\eta_s = (1-\kappa_s-\alpha_s)\times\frac{A}{A+B} \quad \text{and} \quad \lambda_s = (1-\kappa_s-\alpha_s)\times\frac{B}{A+B}$$

with A the expenditure share of COGS on energy, and B the expenditure share of COGS on labor and other variable inputs. Using the ratio of R&D spending on COGS, our estimates of η_s and λ_s , we can compute α_s by combining the first-order condition for research (51) and capital (47), and the expression for operating profits (34), $\alpha_s = \frac{(\delta_a+r)}{\delta_a}(\eta_s+\lambda_s)\frac{\text{R\& D spending}}{\text{COGS}}$. Using again the assumption of CRS we obtain κ_s as follows: $\kappa_s = 1-\alpha_s-\lambda_s-\eta_s$.

For the knowledge spillover parameter ρ, we follow Griliches (1992) who reviews the literature and Bloom et al. (2013) who provide estimates of the social and private

[38]We use value added shares reported by the OECD (https://data.oecd.org/natincome/value-added-by-activity.htm)

returns of R&D. Their estimates imply an industry-wide R&D elasticity of output of the same order of magnitude (between half and double) as the elasticity to the firm-specific stock of R&D. We therefore assume that both parameters are equal in each sector and country, i.e. $\rho_s = \alpha_s$.

We then assume that the productivity of vintages grows at a constant rate over time, denoted g_v, and that there is a simple relationship between the age of the capital stock and the productivity of vintages given by

$$v(\text{age of capital}_i) = v_0(1+g_v)^{-\text{age of capital}_i}. \tag{56}$$

We estimate g_v by running a regression of firms' productivity (TFPR), which we construct using our previous parameters, on the age of the capital stock, and other controls such as the share of intangibles, and total log sales. As can be seen from combining Equation 19 and Equation 56 and shown in Appendix A1.3.1, the coefficient on the age of the capital stock is related one-for-one to g_v. We estimate a 11.9% growth rate in the productivity of capital goods every year, which is consistent with values found in the literature analyzing the contribution of improvements in capital goods to long-run growth, Greenwood et al. (1997).

To estimate the elasticity of emissions to capital vintage, ϵ_v, we start from equation (5): $\log\left[\frac{\text{Emission}}{\text{Energy}}\right] = \log(\phi_s) - \epsilon_v \log v$. We thus run the following regression (see Table A1) with sector, country, and time fixed effects:

$$\log\left[\frac{\text{Emission}_{it}}{\text{Energy}_{it}}\right] = b_s + b_j + b_t + b_{age} \times \text{Age of Capital}_{it} + \epsilon_{sjti}. \tag{57}$$

We then compute ϵ_v as $\epsilon_v = \frac{\hat{b}_{age}}{\log(1+g_v)}$ and $\phi_s = \exp(b_s + b_j)$.

The joint distribution of γ and ξ from which firms draw their initial characteristics upon entering, $G(\gamma,\xi)$, is estimated as follows: we first estimate the pair (γ_i, ξ_i) for each firm within a sector (see below), we then define the sample space as $\{\gamma_i\}_{i\in\Omega_s} \times \{\xi_i\}_{i\in\Omega_s}$ and assume that the probability that a potential entrant draws any pair in this set is uniform: $G(\gamma,\xi) \sim U\left(\{\gamma_i\}_{i\in\Omega_s} \times \{\xi_i\}_{i\in\Omega_s}\right)$.

The cost of operating a firm, κ_f, is common to all firms in a country and is calibrated so that the least profitable firm in a given country is indifferent between staying and exiting the market. The cost of starting a business is common to all firms in a sector and is calibrated so that a potential entrant is indifferent between entering and not, i.e.

$\hat{\kappa}_e = \mathbb{E}_{\hat{G}_s}\left[\mathcal{V}_{si}(k_{V_s}, V_s, \gamma, \xi)\right]$ where we use our estimated distribution G_s to compute the expectation and the value function $\mathcal{V}_{si}(.,.,.,.)$ is obtained by solving the model.

A2.2 Internal Calibration of Firm-specific Variables

In the last step of the calibration, we estimate the three firm-level state variables v, γ, and ξ to match three firm-level moments. The research-efficiency parameter, γ, is calibrated to match the ratio of intangibles over tangible assets, and is given by:[39]

$$\gamma = \frac{1}{\text{Ratio of Intangibles over Tangibles}} \frac{(r+\delta_k)}{(r+\delta_a)\delta_a^{\frac{1}{\alpha_s-1}}} \frac{\alpha_s}{w\kappa_s}. \tag{58}$$

As we have explained above, the productivity of vintages is assumed to grow at a constant rate over time, g_v, so that we can estimate v based on the age of the capital stock using $v = (1+g_v)^{-\text{age of capital}_i}$.

To calibrate the consumers' taste, we use the relationship between the relative size of the firm and the relative vintage productivity, research efficiency, and consumers' taste. Given our estimates of γ and of v from the previous steps, we can recover ξ as follows:

$$\ln\left[\frac{\xi_{si}}{\xi_{sj}}\right] = \ln\left[\frac{\text{COGS}_i}{\text{COGS}_j}\right] - \alpha_s(\sigma_s - 1)\ln\frac{\gamma_j}{\gamma_i} + \kappa_s(\sigma_s-1)\ln\left[1+g_v\right](\text{age of capital}_i - \text{age of capital}_j) \tag{59}$$

We normalize the levels of ξ such that the mean across firms within each sector is 1.

A2.3 Research efficiency parameter

We show that the firm research efficiency parameter, γ, is inversely related to the ratio of intangibles over tangibles assets:

$$\gamma = \frac{1}{\text{Ratio of Intangibles over Tangibles}} \frac{(r+\delta_k)}{(r+\delta_a)\delta_a^{\frac{1}{\alpha_s-1}}} \frac{\alpha_s}{w\kappa_s} \tag{60}$$

We set $\tau_a = 0$ and normalize $w = 1$.

[39] Proofs can be found in Appendix A2.

Proof. We start from the following equations

$$w\ell_a = \frac{(r+\delta_k)\delta_a q_v k_v}{(r+\delta_a)(1-\tau_a)} \frac{\alpha_s}{\kappa_s}$$
$$a = \left(\frac{\ell_a}{\gamma}\right)^{\alpha} \frac{1}{\delta_a}$$

Combining these two gives the following expression for the ratio of intangibles over tangible capitals $a^{1/\alpha_s}/qk$:

$$\frac{a^{\frac{1}{\alpha_s}}}{q_v k_v} = \frac{\ell_a}{\gamma \delta_a^{\frac{1}{\alpha_s}} q_v k_v} = \frac{(r+\delta_k)}{(r+\delta_a)\gamma\delta_a^{\frac{1}{\alpha_s-1}}} \frac{\alpha_s}{w\kappa_s}$$

□

A2.4 Consumers' taste parameter

We now want to derive the following expression when the carbon tax is 0:

$$\ln\left[\frac{\xi_{si}}{\xi_{sj}}\right] = \ln\left[\frac{\text{COGS}_i}{\text{COGS}_j}\right] - \alpha_s(\sigma_s - 1)\ln\frac{\gamma_j}{\gamma_i} + \kappa_s(\sigma_s-1)\ln\left[1+g_v\right](\text{age of capital}_i - \text{age of capital}_j)$$

Proof. We start from the following set of equilibrium conditions and definitions

$$k_v = \left[\frac{\kappa_s(r+\delta_a)w(1-\tau_a)}{\alpha_s(r+\delta_k)\delta_a q_v}\right]^{\frac{1-\hat{\alpha}_s}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \left[\frac{\Omega_{sv\xi}\hat{\alpha}_s}{w(1-\tau_a)(r+\delta_a)\gamma^{\hat{\alpha}}\hat{\delta}_a}\right]^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}}$$
$$\Omega_{sv\xi} k_v^{\hat{\kappa}_s} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}} = \left(\frac{\sigma_s}{\sigma_s-1}\frac{1}{(\eta_s+\lambda_s)} - 1\right) C$$
$$\Omega_{sv\xi} = \left[\frac{\sigma-1}{\sigma}(1+\tau_y)(\lambda_s+\eta_s)P_s(\xi_{si}Y_s)^{\frac{1}{\sigma}}\right]^{\frac{\sigma}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}} \left(\frac{\sigma}{\sigma-1}\frac{1}{(\eta_s+\lambda_s)} - 1\right) \tilde{\Gamma}_{sv}^{\frac{(1-\sigma)(\eta_s+\lambda_s)}{\sigma+(1-\sigma)(\eta_s+\lambda_s)}}$$

Consider a pair of firms i and j within the same country and sector. Combining the expression above gives

$$
\begin{aligned}
C &= \frac{\Omega_{sv\xi} k_v^{\hat{\kappa}_s} a^{\frac{1}{\frac{\sigma}{\sigma-1}-(\eta_s+\lambda_s)}}}{\left(\frac{\sigma_s}{\sigma_s-1}\frac{1}{(\eta_s+\lambda_s)}-1\right)} = \frac{\frac{q_v(r+\delta_k)}{\hat{\kappa}_s} k_v}{\left(\frac{\sigma_s}{\sigma_s-1}\frac{1}{(\eta_s+\lambda_s)}-1\right)} \\
C_i/C_j &= \frac{k_{vi}}{k_{vj}} \\
&= \left(\frac{\Omega_{sv\xi j}\gamma_j^{\hat{\alpha}}}{\Omega_{svi}\gamma_j^{\hat{\alpha}}}\right)^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \\
&= \left(\frac{\xi_{si}^{\frac{1}{\sigma_s+(1-\sigma_s)(\lambda_s+\eta_s)}} \tilde{\Gamma}_{svi}^{\frac{(1-\sigma_s)(\lambda_s+\eta_s)}{\sigma_s+(1-\sigma_s)(\eta_s+\lambda_s)}} \gamma_j^{\hat{\alpha}}}{\xi_{sj}^{\frac{1}{\sigma_s+(1-\sigma_s)(\lambda_s+\eta_s)}\gamma_j^{\hat{\alpha}}} \tilde{\Gamma}_{svj}^{\frac{(1-\sigma_s)(\lambda_s+\eta_s)}{\sigma_s+(1-\sigma_s)(\eta_s+\lambda_s)}} \gamma_i^{\hat{\alpha}}}\right)^{\frac{1}{1-\hat{\kappa}_s-\hat{\alpha}_s}} \\
&= \frac{\xi_{si}\tilde{\Gamma}_{svi}^{(1-\sigma_s)(\lambda_s+\eta_s)}\gamma_j^{\alpha(\sigma-1)}}{\xi_{sj}\tilde{\Gamma}_{svj}^{(1-\sigma_s)(\lambda_s+\eta_s)}\gamma_i^{\alpha(\sigma-1)}} \\
&= \frac{\xi_{si} v_{svi}^{(\sigma_s-1)\kappa_s}\gamma_j^{\alpha_s(\sigma-1)}}{\xi_{sj} v_{svj}^{(\sigma_s-1)\kappa_s}\gamma_i^{\alpha_s(\sigma-1)}}
\end{aligned}
$$

where we assume that the carbon tax is zero or negligible relative to the price of energy. Taking logs gives the result.

□

A2.5 Elasticity of emissions to capital vintage

Below we show the regression with sector, country, and time fixed effects:

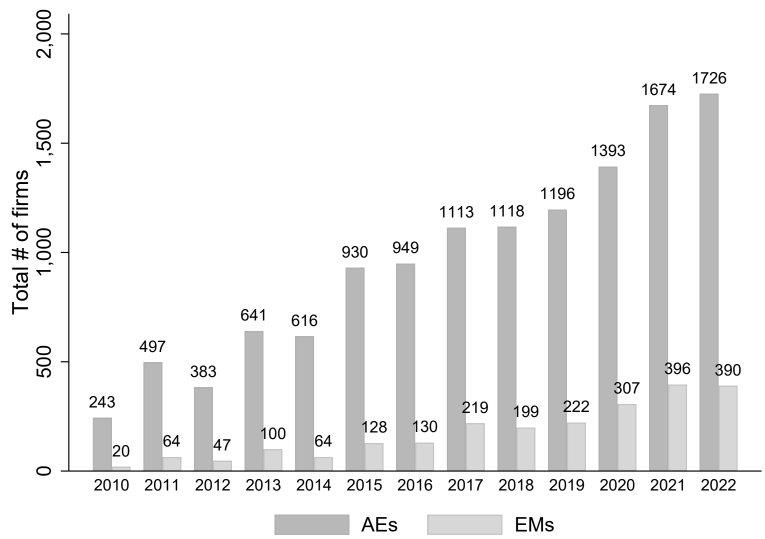
Table A1: Calibration Elasticity of Emissions to Capital Vintages

	(1) log (S1S2 / Energy)
Age of capital	0.04**
	(0.02)
N	5,467
R^2	0.00
Adj-R^2	-0.02
Industry+country+year FE	Yes

Notes: Industry classification: SIC-2. Standard errors in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

A3 Annex: Figures and Tables

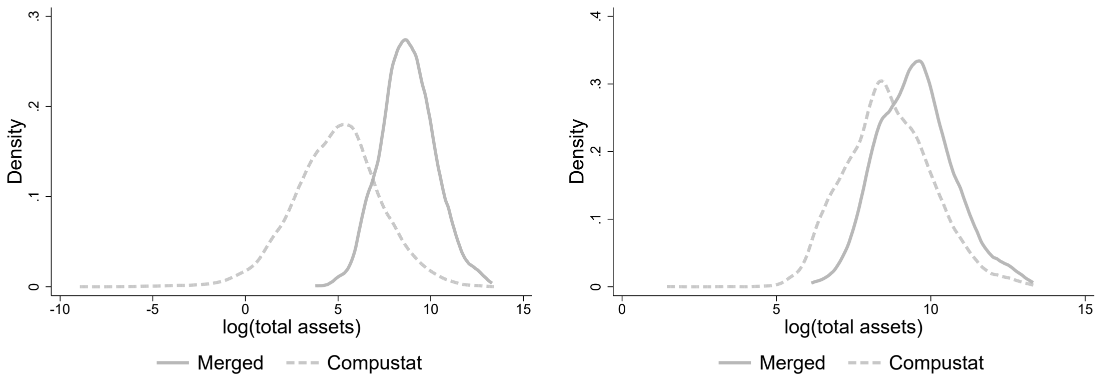
Figure A1: Sample Over Time



Notes: This figure plots the number of firms in the matched Compustat-ICE Data Services sample over time (with non-missing emission intensity) for firms headquartered in advanced economies (AE) and emerging markets (EM). Finance, public administration, and utilities sectors are excluded.

Figure A2: Firm Size: Compustat vs Compustat-ICE Data Services Merged Sample

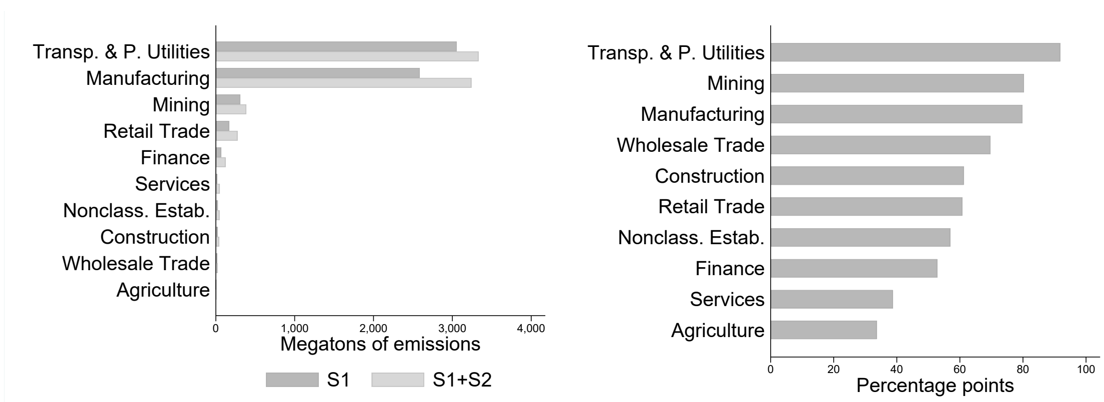
(a) All firms | (b) Among the top 10% by size



Notes: This figure illustrates the size distribution (log assets) for the Compustat and Compustat-ICE Data Services merged samples. Finance, public administration, and utilities sectors are excluded.

Figure A3: Emissions by Industry

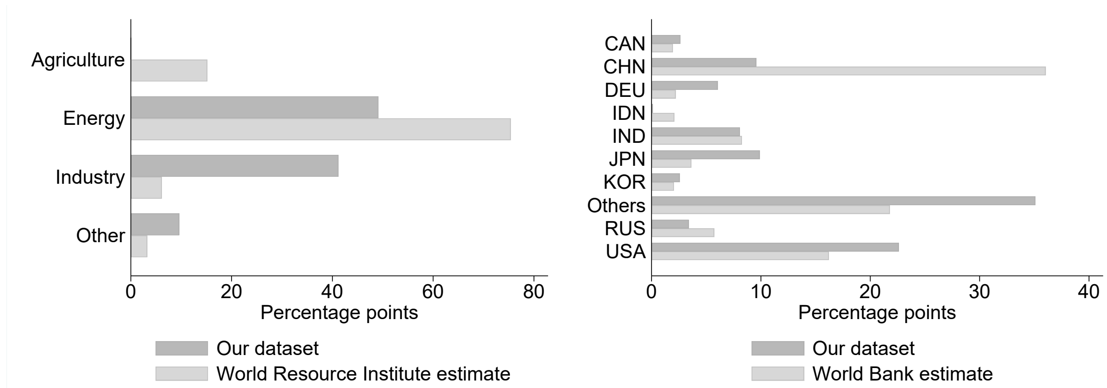
(a) Total emissions | (b) Share of scope 1 over scope 1 plus 2 emissions



Notes: For each industry, panel (a) shows the total emissions generated, while panel (b) plots the shares of scope 1 over scope 1 plus 2 emissions. S1 = scope 1; S1S2 = scopes 1 and 2. Data by all firms in the merged dataset for the year 2019 are used. Agriculture = Agriculture, Forestry, & Fishing; Transp. & P. Utilities = Transportation & Public Utilities; Finance = Finance, Insurance, & Real Estate; Nonclass. Estab. = Nonclassifiable Establishments. 2019 data is used.

Figure A4: Total Emissions: Compustat-ICE Data Services Merged Sample vs Other Sources

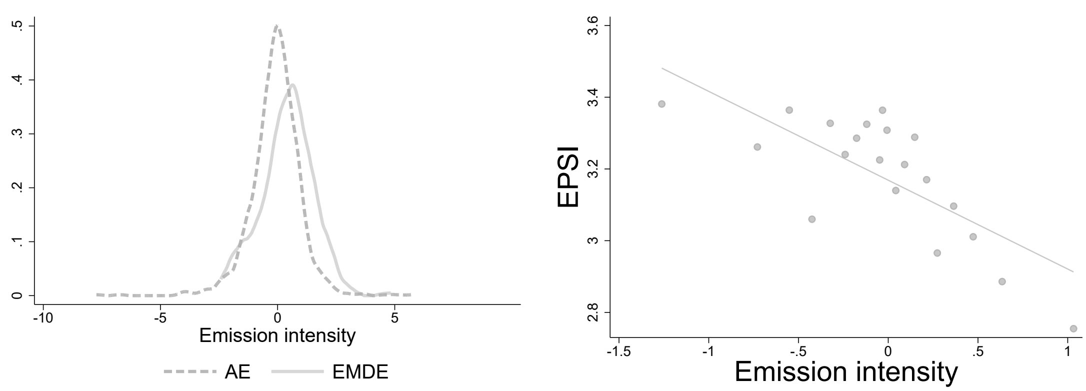
(a) By industry (b) By country



Notes: Panel (a) compares the shares of total scope 1 emissions emanating from each industry group. Panel (b) compares the shares of total scopes 1 and 2 emissions emanating from each country. 2019 data is used.

Figure A5: Hetereogeneity in Emission Intensity: Within Industry and Across Countries

(a) AEs vs EMDEs (b) Emission Intensity and Environmental Policy

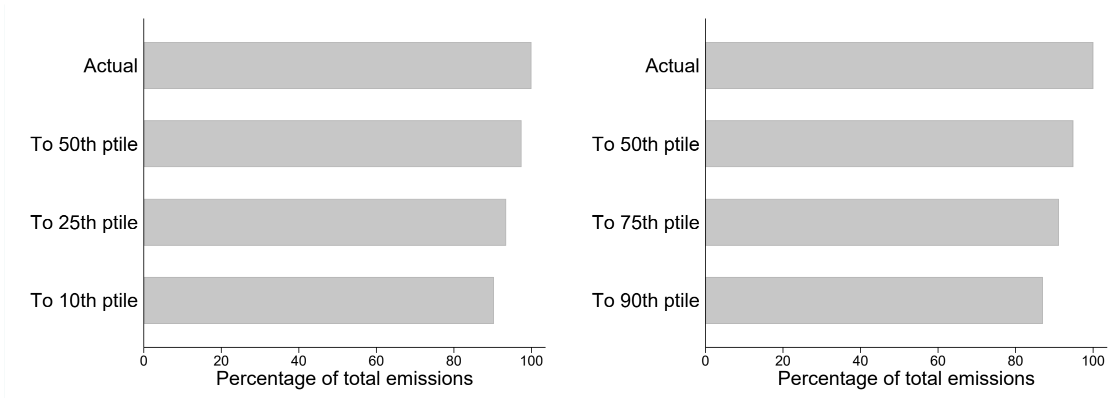


Notes: Emission intensity is measured as the log of emissions over revenues. We residualize the variable against industry fixed effects (4-digit SIC), to allow for cross-country comparisons (while Figure 1 controls for industry *times country* fixed effects). Finance, insurance, real state, public administration, utilities, railroad transportation, and local and interurban passenger transit sectors are excluded from the calculation. 2019 data is used. Panel (a) plots the kernel density of residualized firm emission intensity separately for firms headquartered in AEs and in EMDEs. Panel (b) plots a binned scatterplot of residualized firm emission intensity against the Environmental Policy Stringency Index (EPSI) of OECD for the country where the firm is headquartered.

Figure A6: Emission Counterfactuals for Specific Channels

(a) Age of Capital

(b) Share of Intangible Capital



Notes: This figure illustrates actual emissions of firms in our sample, together with the counterfactual emissions that we would observe if every firm (a) had at most the same age of capital as the firm in the Xth percentile and (b) had at least the same knowledge intensity (share of intangible capital) as the firm in the percentile. Only industry-country groups with at least 4 firms are included in panel. 4-digit SIC industry classification and 2019 data used. Finance, public administration, and utilities sectors are excluded from the calculation.

Table A2: Emissions over Energy and Firm Characteristics: Alternative Industry Classifications

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Emissions over Energy (Log emissions / energy)							
Age of capital	0.10***	0.10***	0.10***	0.03**	0.03**	0.09***	0.07***	0.14***
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)	(0.04)
Share intangibles	-0.01	-0.00	-0.00	0.08***	0.07***	0.01	0.01	0.05
	(0.03)	(0.03)	(0.03)	(0.02)	(0.01)	(0.02)	(0.02)	(0.04)
TFP	0.02	0.02	0.01	-0.08***	-0.09***	0.01	-0.01	0.06
	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)	(0.05)
Log(assets)	-0.07**	-0.07**	-0.06**	0.02	0.03**	-0.05**	-0.03	-0.08*
	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.03)	(0.02)	(0.04)
N	2,690	2,690	2,690	6,142	6,142	3,489	3,489	938
R^2	0.51	0.49	0.42	0.35	0.29	0.46	0.33	0.38
Adj-R^2	0.23	0.23	0.22	0.17	0.15	0.19	0.19	0.12
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry classification	SIC4	SIC3	SIC2	GICS4	GICS2	NAICS4	NAICS2	HP

Notes: Industry classification: SIC4 = 4-digit Standard Industrial Classification; GICS2 = 2-digit Global Industry Classification Standard; NAICS6 = 6-digit North American Industry Classification System; HP = Hoberg-Phillips 500. All variables are standardized to have mean zero and standard deviation of one. All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Energy, utilities, finance, and public sectors are excluded from the calculations. * $p < .1$, ** $p < .05$, *** $p < .01$

Table A3: Emission Intensity and Firm Characteristics: Alternative Indicators

	(1)	(2)	(3)	(4)
	Emission Intensity (Log emissions / revenue(t-1))			
Age	0.04***			0.04***
	(0.01)			(0.01)
Log(RD / assets)		-0.07***		-0.07***
		(0.02)		(0.02)
Log(EBIT/assets)			-0.05***	-0.05***
			(0.01)	(0.01)
Log(assets)	0.03*	0.03***	0.04***	0.01
	(0.01)	(0.01)	(0.01)	(0.01)
N	6,204	6,204	6,204	6,204
R^2	0.79	0.79	0.79	0.80
Adj-R^2	0.68	0.68	0.68	0.68
Industry × country × year FE	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. By including only industry × country × year groups with more than one firm, our sample size is reduced from 13,492 to 6,204. * $p < .1$, ** $p < .05$, *** $p < .01$

Table A4: Emissions over Energy and Firm Characteristics: Alternative Indicators

	(1)	(2)	(3)	(4)
	Emissions over Energy (Log emissions / energy)			
Age	0.05***			0.05***
	(0.02)			(0.02)
Log(RD / assets)		-0.05		-0.07**
		(0.03)		(0.03)
Log(EBIT/assets)			0.03	0.03
			(0.02)	(0.02)
Log(assets)	-0.13***	-0.11***	-0.10***	-0.13***
	(0.03)	(0.03)	(0.03)	(0.03)
N	2,566	2,566	2,566	2,566
R^2	0.52	0.52	0.52	0.52
Adj-R^2	0.23	0.23	0.23	0.23
Industry × country × year FE	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. By including only industry × country × year groups with more than one firm, our sample size is reduced from 7,026 to 2,566. * $p < .1$, ** $p < .05$, *** $p < .01$

Table A5: Emission Intensity and Firm Characteristics: Robustness

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	Emission Intensity (Log emissions / revenue(t-1))															
	Largest 50% of firms				Adding financial controls				Removing the Covid period				Scope 1 emissions			
Age of capital	0.05**			0.04*	0.05***			0.03**	0.07***			0.04***	0.04***			0.02*
	(0.02)			(0.02)	(0.02)			(0.02)	(0.02)			(0.02)	(0.01)			(0.01)
Share intangibles		-0.16***		-0.13***		-0.23***		-0.20***		-0.17***		-0.14***		-0.15***		-0.12***
		(0.02)		(0.02)		(0.02)		(0.02)		(0.02)		(0.02)		(0.01)		(0.01)
TFP			-0.15***	-0.10***			-0.17***	-0.11***			-0.18***	-0.14***			-0.15***	-0.11***
			(0.02)	(0.02)			(0.02)	(0.02)			(0.02)	(0.02)			(0.01)	(0.01)
Log(assets)	0.02	0.04	0.04	0.04	0.30***	0.45***	0.34***	0.46***	0.05***	0.09***	0.13***	0.13***	0.08***	0.11***	0.15***	0.15***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.05)	(0.05)	(0.05)	(0.05)	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
N	2,515	2,515	2,515	2,515	3,774	3,774	3,774	3,774	3,541	3,541	3,541	3,541	6,092	6,092	6,092	6,092
R^2	0.81	0.82	0.82	0.83	0.83	0.85	0.84	0.85	0.80	0.81	0.81	0.82	0.83	0.83	0.83	0.84
Adj-R^2	0.70	0.72	0.71	0.72	0.73	0.76	0.75	0.77	0.69	0.71	0.71	0.72	0.73	0.74	0.74	0.75
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. Financial controls include lagged liquidity, leverage, and capitalization ratios, and the market share. The Covid period is defined as 2020 and afterwards. By including only industry × country × year groups with more than one firm, our sample size is reduced from 6,953 to 2,515 for regressions (1-4), from 9,270 to 3,774 for regressions (5-8), from 8,305 to 3,541 for regressions (9-12), and from 13,158 to 6,092 for regressions (13-16). * $p < .1$, ** $p < .05$, *** $p < .01$

Table A6: Emissions over Energy and Firm Characteristics: Robustness

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	Emissions over Energy (Log emissions / energy)															
	Largest 50% of firms				Adding financial controls				Removing the Covid period				Scope 1 emissions			
Age of capital	0.04			0.04	0.04			0.04	0.11***			0.12***	0.04*			0.05**
	(0.03)			(0.03)	(0.03)			(0.04)	(0.03)			(0.03)	(0.02)			(0.02)
Share intangibles		0.05		0.03		0.05		0.02		-0.01		-0.02		0.00		-0.02
		(0.04)		(0.04)		(0.03)		(0.03)		(0.03)		(0.03)		(0.03)		(0.03)
TFP			0.05	0.04			0.06*	0.06			-0.00	0.01			0.04*	0.05**
			(0.04)	(0.04)			(0.03)	(0.04)			(0.03)	(0.03)			(0.02)	(0.02)
Log(assets)	-0.09*	-0.10*	-0.09*	-0.10*	-0.11	-0.15	-0.13	-0.15	-0.07**	-0.06**	-0.06*	-0.07**	0.03	0.03	0.02	0.02
	(0.05)	(0.05)	(0.05)	(0.05)	(0.11)	(0.11)	(0.11)	(0.11)	(0.03)	(0.03)	(0.03)	(0.03)	(0.02)	(0.02)	(0.02)	(0.03)
N	1,265	1,265	1,265	1,265	1,549	1,549	1,549	1,549	2,165	2,165	2,165	2,165	2,463	2,463	2,463	2,463
R^2	0.47	0.47	0.47	0.47	0.55	0.55	0.55	0.55	0.51	0.50	0.50	0.51	0.66	0.66	0.66	0.66
Adj-R^2	0.14	0.14	0.14	0.14	0.26	0.26	0.26	0.26	0.22	0.21	0.21	0.22	0.45	0.45	0.45	0.45
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. Financial controls include lagged liquidity, leverage, capitalization ratios, and the market share. The Covid period is defines as 2022 and afterwards. By including only industry × country × year groups with more than one firm, our sample size is reduced from 4,191 to 1,265 for regressions (1-4), from 4,704 to 1,549 for regressions (5-8), from 6,012 to 2,165 for regressions (9-12), and from 6,705 to 2,463 for regressions (13-16). * $p < .1$, ** $p < .05$, *** $p < .01$

Table A7: Emission Intensity and Firm Characteristics: AEs vs EMDEs

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Emission Intensity (Log emissions / revenue(t-1))							
	Advanced economies				Emerging markets			
Age of capital	0.04***			0.02*	0.18***			0.17***
	(0.01)			(0.01)	(0.05)			(0.05)
Share intangibles		-0.16***		-0.13***		-0.22***		-0.14***
		(0.01)		(0.01)		(0.05)		(0.04)
TFP			-0.18***	-0.15***			-0.32***	-0.27***
			(0.01)	(0.01)			(0.05)	(0.05)
Log(assets)	0.04***	0.08***	0.11***	0.13***	0.02	0.07	0.22***	0.22***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.05)	(0.05)	(0.06)	(0.06)
N	6,050	5,876	5,988	5,791	799	766	795	743
R^2	0.79	0.80	0.80	0.81	0.79	0.79	0.81	0.81
Adj-R^2	0.68	0.70	0.70	0.72	0.64	0.63	0.68	0.67
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. * $p < .1$, ** $p < .05$, *** $p < .01$

Table A8: Emission Intensity and Firm Characteristics: Emission Intensity Computed Using Total Assets and Value Added

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Emission Intensity (Log emissions / assets(t-1))				Emission Intensity (Log emissions / value added(t-1))			
Age of capital	0.07***			0.05***	0.16***			0.10***
	(0.01)			(0.01)	(0.03)			(0.03)
Share intangibles		-0.19***		-0.16***		-0.35***		-0.24***
		(0.01)		(0.01)		(0.03)		(0.03)
TFPR			-0.14***	-0.09***			-0.51***	-0.43***
			(0.01)	(0.01)			(0.04)	(0.04)
Log(assets)	-0.02**	0.02**	0.04***	0.05***	-0.03	0.05*	0.17***	0.19***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.03)	(0.03)	(0.03)	(0.03)
N	6,537	6,537	6,537	6,537	5,575	5,575	5,575	5,575
R^2	0.79	0.81	0.80	0.82	0.79	0.80	0.81	0.81
Adj-R^2	0.68	0.71	0.69	0.72	0.68	0.69	0.70	0.71
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the country × industry × year. Finance, public administration, and utilities sectors are excluded from the calculations. By including only industry × country × year groups with more than one firm, our sample size is reduced from 13,950 to 6,537 in columns (1-4) and from 12,308 to 5,617 in columns (5-8). * $p < .1$, ** $p < .05$, *** $p < .01$

Table A9: Emissions and Firm Characteristics: Firm-level clustering

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Emission Intensity (Log emissions / revenue(t-1))				Emissions over Energy (Log emissions / energy)			
Age of capital	0.05**			0.03	0.10***			0.10***
	(0.02)			(0.02)	(0.03)			(0.03)
Share intangibles		-0.17***		-0.13***		-0.00		-0.01
		(0.02)		(0.02)		(0.04)		(0.04)
TFPR			-0.20***	-0.16***			0.01	0.02
			(0.03)	(0.03)			(0.05)	(0.05)
Log(assets)	0.04*	0.08***	0.13***	0.14***	-0.07	-0.06	-0.06	-0.07
	(0.02)	(0.02)	(0.03)	(0.03)	(0.05)	(0.05)	(0.06)	(0.06)
N	6,534	6,534	6,534	6,534	2,690	2,690	2,690	2,690
R^2	0.80	0.81	0.82	0.82	0.51	0.51	0.51	0.51
Adj-R^2	0.70	0.71	0.72	0.73	0.23	0.22	0.22	0.23
Industry × country × year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: All variables are standardized to have mean zero and standard deviation of one. Standard errors in parentheses, clustered at the firm level. Finance, public administration, and utilities sectors are excluded from the calculations. By including only industry × country × year groups with more than one firm, our sample size is reduced from 13,947 to 6,534 in columns (1-4) and from 7,215 to 2,690 in columns (5-8). * $p < .1$, ** $p < .05$, *** $p < .01$

To further test whether improved production processes help lower emissions per unit of output, we analyze whether better management practices, as captured by the World Management Survey (Bloom and Van Reenen, 2007), are related to lower emission intensities. We estimate the following linear model:

$$\widetilde{EI}_{i,t} = \widetilde{MS}_i \beta + \widetilde{Assets}_{i,t} \gamma + \epsilon_{i,t} \tag{61}$$

$\widetilde{EI}_{i,t}$ are residualized log emission intensities, that is, the residuals resulting from regressing log emission intensities on a set of country × industry × year dummies. $\widetilde{MS}_i$ is the (residualized) overall management score of firm i according to the World Management Survey.[40] (Residualized) log assets are used to control for size. Before residualizing, all variables are standardized to have mean zero and standard deviation of one. As reported in Table A10, firms with higher management scores have lower emission intensity with respect to other firms in the same industry. These results support our hypothesis, and are in line with Bloom et al. (2010).

Table A10: Emission Intensity and Management Practices

	(1)	(2)
	Emission Intensity (STD log emissions / revenue(t-1))	
Management score	-0.465***	-0.532***
	(0.149)	(0.189)
STD log(assets)		0.107
		(0.088)
N	92	92
R^2	0.191	0.193
Adj-R^2	0.182	0.175

Notes: Robust standard errors in parentheses. Intensity and assets residualized against SIC3-country-year fixed effects, management scores are residualized against SIC3-country-wave fixed effects. * $p < .1$, ** $p < .05$, *** $p < .01$

[40] World Management Survey data is only available for a small subset of the US manufacturing firms in the sample (23 firms). Given the small sample size, we cannot include the fine set of fixed effects directly in the regression. Therefore, for emission intensities and total assets we first obtain the residuals of the variables against the fine set of fixed effects from a regression including all the firms in the matched Compustat-ICE data. For the management score, we use the score of the latest survey wave at our disposal, which is 2015 for most firms. We residualize this variable against country × industry dummies, from a regression including all firms in the World Management Survey data. We then include these residuals in Equation 61.

Table A11: Emission Intensity and Age of Capital: Growth Rate of Assets

	Emission Intensity (OLS)	Age of capital (First stage)	Emission Intensity	Emission Intensity (2SLS)
Age of capital	0.0198*			0.112***
	(0.0106)			(0.0408)
5-yr growth rate assets		-1.336***	-0.149***	
		(0.0954)	(0.0542)	
N	4,262	4,262	4,262	4,262
R^2	0.849	0.629	0.849	0.086
Industry × Year × Country FE	Yes	Yes	Yes	Yes

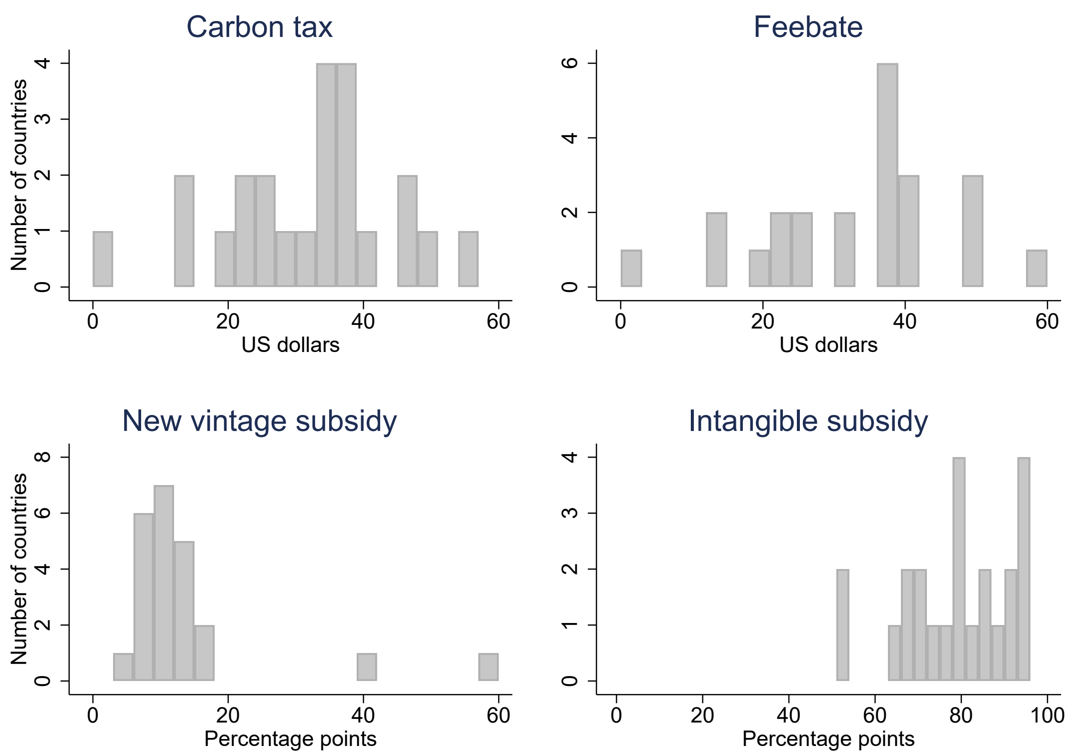
Notes: All regressions include TFP and size of the firm as control (measured with the level of assets, in logs). For the last regression, the F-statistics first stage is 368.06. Standard errors clustered at Industry × year × country (using SIC4 industry classification), * $p < .1$, ** $p < .05$, *** $p < .01$

Table A12: Emission Intensity and Age of Capital: Growth Rate of Sales

	Emission Intensity (OLS)	Age of capital (First stage)	Emission Intensity	Emission Intensity (2SLS)
Age of capital	0.0203*			0.135***
	(0.0106)			(0.0402)
5-yr growth rate sales		-1.401***	-0.189***	
		(0.102)	(0.0548)	
N	4,254	4,254	4,254	4,254
R^2	0.849	0.627	0.850	0.068
Industry × Year × Country FE	Yes	Yes	Yes	Yes

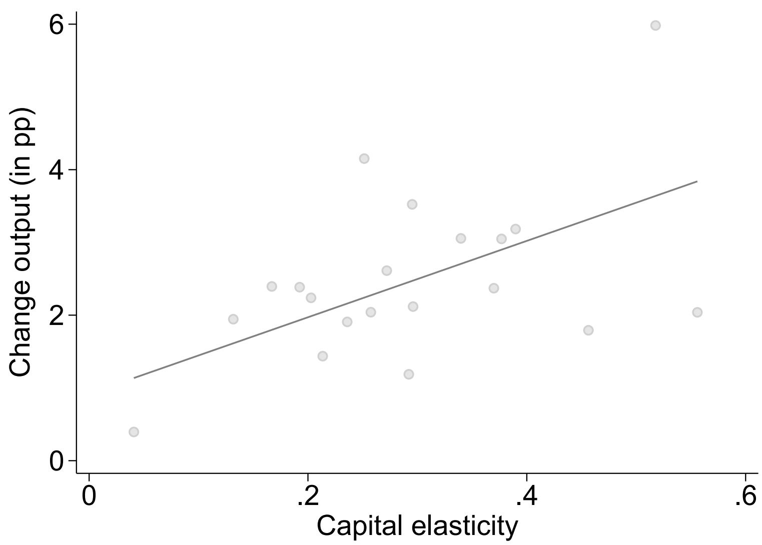
Notes: All regressions include TFP and size of the firm as control (measured with the level of assets, in logs). For the last regression, the F-statistics first stage is 357.42 . Standard errors clustered at Industry × year × country (using SIC4 industry classification), * $p < .1$, ** $p < .05$, *** $p < .01$

Figure A7: Distribution of Taxes and Subsidies in Counterfactuals



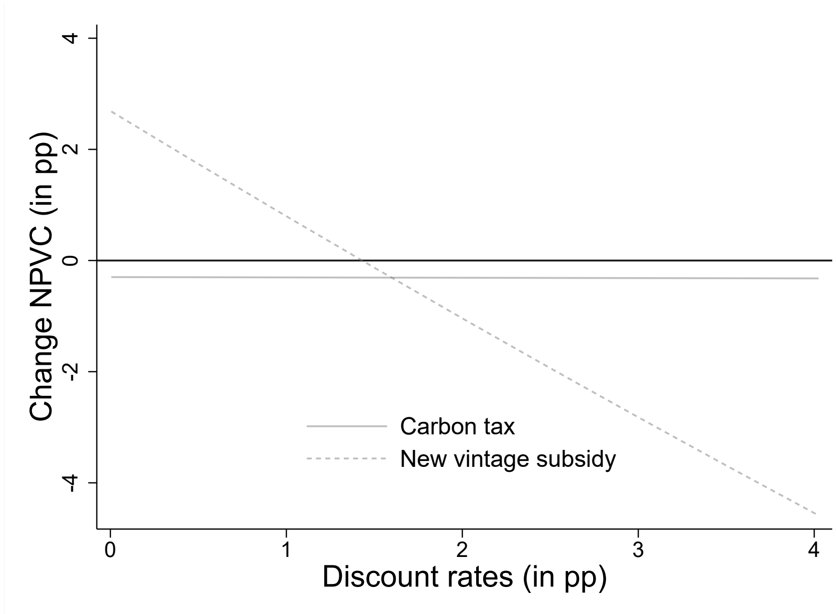
Notes: For each policy instrument, we solve for the value it should take in each country (in US dollars or percentage points) to achieve a 15% reduction in emissions relative to the baseline (a no-policy scenario). Each histogram shows, for a different policy, the number of countries (y-axis) for which each policy value (x-axis) is necessary to achieve the emissions reduction target.

Figure A8: Relationship Between Capital Elasticity and Effect on GDP of Capital Subsidies



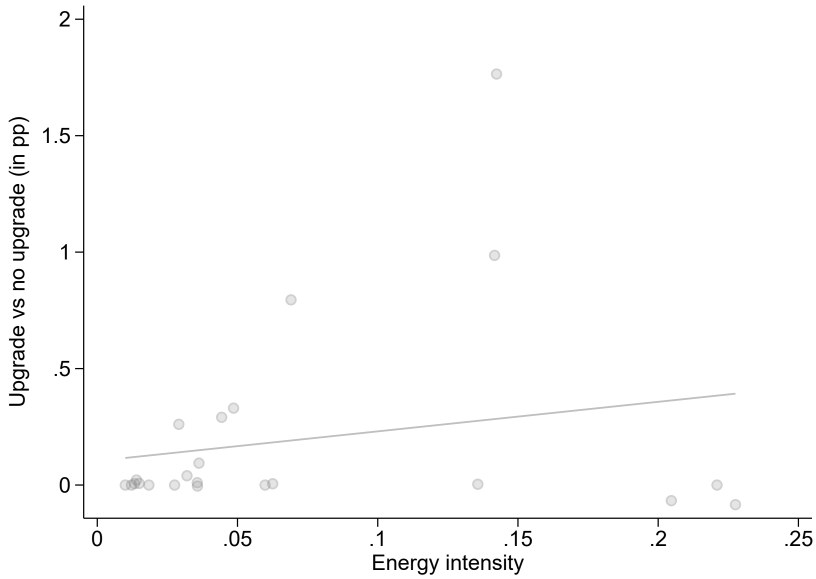
Notes: This plot shows a binscatter plot for the cross-section of countries of the average capital elasticity of output and the changes in the steady-state output with respect to the baseline after a capital subsidy calibrated such that emissions decrease by 15%.

Figure A9: Present Value Consumption Costs Under Varying Planner Discount Rates



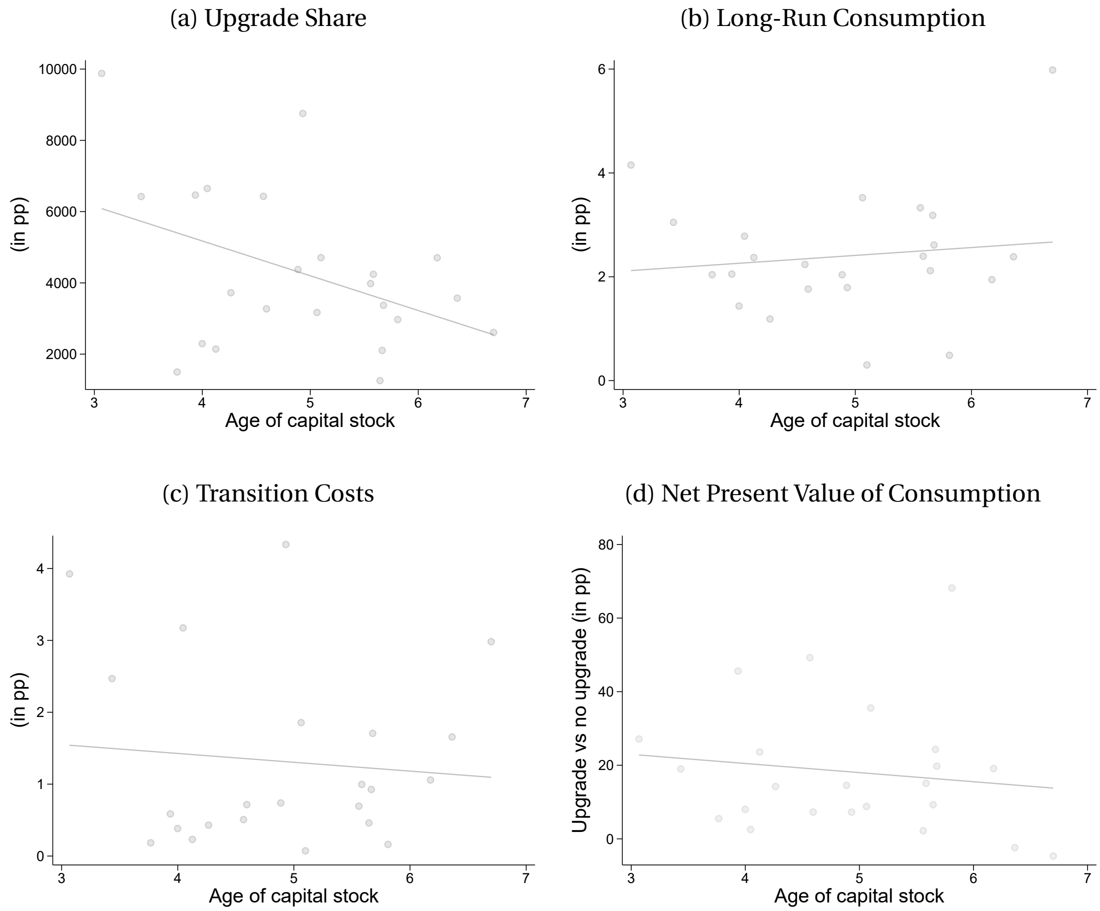
Notes: This plot compares the net present value of consumption (NPVC) costs of a capital subsidy and a carbon tax under varying planner discount rates, given a market discounty rate of 4%. Both policies are calibrated such that emissions decrease by 15%.

Figure A10: Counterfactual Analysis of Carbon Taxes: Cross-Country Differences in Energy Intensity and Consumption



Notes: This scatter plot compares average energy intensity and changes in the net present value of consumption (NPVC) across countries, between simulations allowing firms to upgrade capital vintages and those that do not.

Figure A11: Counterfactual Analysis of Capital Subsidies: Cross-Country Differences in Age of Capital Stock and Selected Macroeconomic Variables



Notes: This set of scatter plots compares the average age of capital stock across countries with selected macroeconomic variables. Panel (a) shows the share of firms upgrading (in percentage points), Panel (b) shows changes in long-run consumption (in percentage points) relative to the actual economy, Panel (c) shows transition costs, and Panel (d) compares the net present value of consumption between simulations with and without capital vintage upgrades.

PUBLICATIONS

Mitigating Climate Change at the Firm Level: Mind the Laggards
Working Paper No. WP/2023/242