Corporate Taxation and Carbon Emissions[†]

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Abstract

We study the relationship between corporate taxation and carbon emissions in the U.S. We show that dirty firms pay lower profit taxes. This relationship is driven by dirty firms benefiting disproportionately more from the tax shield of debt due to their higher leverage. In addition, we document that the higher leverage of dirty firms is fully accounted for by the larger share of tangible assets owned by such firms. We build a general-equilibrium multi-sector economy and show that a revenue-neutral increase in profit taxation could lead to large decreases in aggregate carbon emissions without any noticeable change in GDP.

Keywords: Corporate Taxes, Carbon Emissions, Leverage, Asset Tangibility.
JEL Codes: H32, Q58.

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1 Introduction

The corporate income tax is a major source of revenue for the U.S. government,[1] yet its effects on the economy are fiercely debated. Those against it emphasize its adverse impact on investment. Tax cuts on corporate income, they argue, increase aggregate economic activity and tend to be beneficial for the economy. Advocates of corporate income tax, on the other hand, observe that tax rates on large businesses have effectively decreased in the last decades as a byproduct of globalization and international profit shifting, contributing to rising wealth inequality since business ownership is concentrated among the wealthiest individuals. To make things worse, deductions available in the tax code—for instance, firms can deduct interest payments on corporate debt from their profits—create heterogeneity in the tax base and thus lead to a multitude of effective tax rates, which generates distortions and resource misallocation. The empirical and theoretical literature on the effects of corporate taxation on firms' decisions, and on its incidence on shareholders, workers, business reallocation and prices, is large. We know surprisingly little, however, about the impact of corporate taxation on the environment. Do dirty firms face a bigger or smaller tax burden relative to clean firms? And what are the consequences of that for the environment? To the best of our knowledge, we are the first study to address these questions.

[INSERT FIGURE 1]

We uncover a new surprising fact, which is summarized in Figure 1, Panel A. In the cross-section of firms in our sample, there is a strong and negative relationship between profit taxes and carbon emissions (both scaled by sales). This correlation suggests that the U.S. corporate tax code contains an implicit *subsidy* on pollution. The main contribution of this paper is to document this new finding, to investigate its determinants, and to quantify the implications for the environment. In fact, as shown in Panel B of Figure 1, we find that the negative relationship between corporate taxes and carbon emissions is largely driven by the deductibility of interest payments on debt financing. If a tax reform removed the tax advantage of debt, our quantitative general-equilibrium framework implies that economic activity would reallocate from dirty to clean sectors, with quantitatively large reductions in aggregate emissions. More generally, we show that a revenue-neutral increase in profit taxation could lead to a large decrease in aggregate carbon emissions without any noticeable change in GDP.

The empirical analysis presented in the first part of our paper focuses mainly on publicly listed firms in the U.S., from 2004 (when data on firm-level carbon emissions became available) to 2019. We use firms' direct (scope 1) carbon emissions from Trucost and link it to accounting data from Standard & Poor's Compustat. In our baseline specification, we regress taxes on carbon emissions (both scaled by sales) in the cross-section of firms. We find that 1 tonne of carbon is associated with

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[1] In 2021, the U.S. federal government received USD 370 billion in corporate tax revenue, or 1.7% of U.S. GDP (source: Congressional Budget Office). Corporate income taxes are also a major source of revenues in virtually all developed countries.

around 5 to 7 USD lower taxes. We then show that this relationship is almost entirely attributable to the tax shield from debt financing. More specifically, many corporate tax systems—including the U.S. one—allow firms to deduct interest expenses from profit taxes. A measure of the debt tax shield that a firm enjoys is thus given by the firm's interest expenses times the statutory corporate tax rate faced by the firm depending on the (domestic and/or international) location of its activities. We provide evidence that the tax shield of debt benefits dirty firms disproportionately. What is more, there is no significant relationship between carbon intensity and the hypothetical taxes that firms would pay in the absence of the tax shield.[2]

The next step is to show why dirty firms are better equipped at taking advantage of the tax shield of debt. We document that dirty firms tend to have higher debt levels. At the same time, they do not pay a higher cost for borrowing, nor locate their activities in countries or U.S. states with lower tax rates. Since the tax shield of debt equals the product of interest expenses and corporate tax rates, it follows that dirty firms' higher tax shield—and the negative relationship between taxes and carbon emissions—is fully accounted for by the higher leverage of these firms. Dirty firms borrow more, deduct higher interest expenses and pay lower taxes.

We are left to study why dirty firms can sustain a higher leverage. Our analysis uncovers large differences in asset tangibility between clean and dirty firms. Moreover, we confirm a strong positive relationship between asset tangibility and leverage, as documented in a large body of work in corporate finance (e.g., Titman and Wessels (1988) and Rajan and Zingales (1995)). In fact, once we control for the asset tangibility of dirty firms, both the positive correlation between carbon intensity and leverage, and the positive correlation between carbon intensity and the tax shield vanish.

We conduct a battery of tests to verify the robustness of our findings. We find that our results are neither driven by one specific sector nor by a specific time-period; they also hold for private firms and in sub-samples of domestic versus multinational firms. What is more, our estimates are consistent regardless of how we measure firms' carbon emissions: we consider separately self-reported versus estimated emissions, carbon emissions from stationary sources reported to the Environmental Protection Agency (EPA), and including firms' indirect upstream and downstream emissions (scope 2 and 3). Further, our tax shield results are robust to using estimates of firms' marginal instead of statutory tax rates. Finally, we document that while most of the effect stems from differences across industries, the carbon-tangibility-tax-shield nexus operates also within industries, including the energy sector: dirty energy producers (measured by their carbon intensity or their fossil fuel energy production capacity) employ more tangible assets, borrow more, enjoy higher debt tax shields and, as a consequence, pay lower taxes.

To appreciate the economic significance of our findings, we compute the implicit carbon subsidies associated to the existing U.S. corporate taxation scheme. We find them to range around 30 billion USD—an amount of similar magnitude to the carbon-pricing revenues raised by gov-

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[2] Hypothetical taxes are obtained by adding our measure of the tax shield to the actual taxes paid by firms.

ernments worldwide in a given year. Our analysis, therefore, uncovers a quantitatively important channel through which corporate taxation impacts carbon emissions—a channel that has so far been overlooked both in the academic literature and by policymakers.

To quantify the effects of corporate taxes on emissions and to study the implications, for emissions and macroeconomic variables, of alternative policies, we build a rich general-equilibrium model where production generates carbon emissions. To be consistent with our empirical findings, the model incorporates three key features. First, firms belong to different industries, which differ along two dimensions: tangible-capital intensity and carbon intensity. Second, firms are subject to a financial friction linking tangible capital to leverage. This assumption can be motivated by several widely-known theories positing the existence of asymmetric information in credit markets (e.g., Tirole (2010)). In this context, collateral (e.g., tangible capital) relaxes borrowing constraints by alleviating asymmetric information. Finally, the model allows for general-equilibrium forces, which are crucial to assess the implications of economy-wide policy changes.

The model also embodies a rich input/output network structure. Intuitively, if goods produced from carbon-intensive sectors (e.g., energy) are used both as a final good and as an intermediate input, then abstracting from sector linkages is likely to produce incorrect inference about the effects of policies targeting carbon emissions. More specifically, we consider two types of input/output networks. The first type is the standard intermediates network: to produce their output, firms require goods produced by other sectors. The second type is the novel "investment network" (vom Lehn and Winberry, 2021): to produce capital goods firms must also combine output from other sectors. vom Lehn and Winberry (2021) constructs the investment network for one type of capital good (which is a combination of structures, equipment, and intangibles). We extend their analysis and construct three different networks—one for structures, one for equipment and one for intangibles.

The model provides a way to formalize and quantify the implicit subsidy in the corporate tax code. In particular, we show that the tax shield of debt—which, from our empirical analysis is the key driver of the tax advantage of dirty firms—can be interpreted as a combination of two taxes: a *negative* carbon tax (a subsidy to carbon emissions!) and a firm-specific revenue tax. In our first counterfactual we study a tax reform which removes the tax shield of debt. The policy raises firms' user cost of capital, prompting firms to scale down production capacity, reducing output and emissions. The model provides an estimate of both aggregate and sector-level effects of the tax reform. In particular, aggregate output and consumption in the counterfactual economy are, respectively, 2.12% and 1.66% lower. The reduction in aggregate output is accompanied by a decrease in total emissions of 5.37%.

The reason for the large fall in emissions—more than twice as large as the fall in output—lies in the heterogeneous response across sectors. Consistent with our empirical findings, the tax shield of debt in the model favors more polluting sectors, whose production technology requires relatively more tangible capital. It follows that, when the tax advantage of debt is removed, firms in dirty industries experience a relatively higher increase in their user cost of (tangible) capital and, as a result, scale down production by a larger extent. There is thus a *positive correlation* between an industry's emission intensity and the reduction in its output, which is responsible for the substantial decrease in total emissions.

By removing the tax advantage of debt, our policy essentially increases taxes on the corporate sector; government budget is thus affected, and so are GDP and household consumption. In our second counterfactual, we show that the government can appropriately design a subsidy to restore budget balance and increase GDP. A government implementing such a policy mix—i.e., removing the tax shield and introducing the appropriate subsidy—can achieve a fall in total emissions of roughly 2.4% without any noticeable change in government budget or GDP. The reason lies, once again, in the fact that the policy mix varies the composition of aggregate production in favor of cleaner industries.

Our work has important policy implications. Previous work have discussed the distortions driven by the differential tax treatment of debt versus equity (e.g., Stiglitz, 1973; King, 1974). We show that the current tax advantage of debt financing is also implicitly subsidizing pollution, and we quantify the environmental consequences of harmonizing the tax treatment of different sources of financing in a general-equilibrium model. Our work suggests that recent corporate tax reforms will have large consequences for the environment.[3]

Our work relates to several strands of literature. We first contribute to a large body of empirical work on the environmental consequences of taxation, such as carbon taxes (e.g., Bruvoll and Larsen, 2004; Andersson, 2019; Metcalf and Stock, 2020), energy taxes (Parry and Small, 2005) and import tariffs (Shapiro, 2020), and to the literature on the incidence of corporate taxation. While earlier work has focused on the effect of corporate taxes on shareholders (Harberger, 1962; Auerbach, 2006, for a review), more recent studies have estimated the impacts on workers (Fuest, Peichl, and Siegloch, 2018; Suárez Serrato and Zidar, 2016), business reallocation (Giroud and Rauh, 2019), and consumer prices (Baker, Sun, and Yannelis, 2019). Carrizosa, Gaertner, and Lynch (2020); Sanati (2022) estimate the effects of the limitation on the interest payments' deductibility introduced in 2017 in the U.S. on firm leverage, investment, and employment.[4] We are the first paper to focus on the consequences of corporate taxation for firms' carbon emissions.

More generally, our paper adds to the recent literature on the welfare consequences of corporate taxation (Chetty and Saez, 2010; Dávila and Hébert, 2023). In that vein, our contribution is to quantify the environmental consequences of counterfactual corporate taxation systems. For this, we combine insights from the theoretical literature on environmental economics (Bovenberg

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[3] The passage of the 2017 Tax Cuts and Jobs Act in the U.S. was associated with a large reduction in corporate tax rates, and a limitation on the deductibility of interest payments. See also the G7 current discussions about corporate taxation of multinationals, which represent a large fraction of carbon emissions worldwide.

[4] See also House and Shapiro (2008); Yagan (2015); Ohrn (2018); Maffini, Xing, and Devereux (2019); Liu and Mao (2019); Zwick and Mahon (2017); Moon (2022); Boissel and Matray (2022) for recent empirical work estimating the effects of other types of taxes (such as dividend tax), or tax incentives (such as bonus depreciation), on firms' outcomes.

and Goulder, 1996; Acemoglu, Aghion, Bursztyn, and Hemous, 2012; Golosov, Hassler, Krusell, and Tsyvinski, 2014) with the production network literature (Liu, 2019; Baqaee and Farhi, 2019; Bigio and La'O, 2020). King, Tarbush, and Teytelboym (2019); Baylis, Fullerton, and Karney (2013, 2014) study the implications of carbon pricing in multi-sector economies. King, Tarbush, and Teytelboym (2019) show that raising carbon taxes on central sectors allows to obtain larger reductions in aggregate carbon emissions.

We also add to a fast growing literature in climate finance. Giglio, Kelly, and Stroebel (2021) provide a review of the literature exploring the pricing of climate risks for different asset classes. Piazzesi, Papoutsi, and Schneider (2022) document that the recent bond purchases by the ECB have implicitly favored firms with higher carbon emissions. The reason is that the ECB aims to be market neutral, that is, it purchases bonds in proportion to the outstanding market value. Firms in high-emissions sectors, however, issue more bonds due to their larger holdings of tangible assets. Oehmke and Opp (2022) study theoretically the effects of differential capital requirements for loans to brown and green firms. Compared to these papers, we assess the implications of the tax advantage of debt for carbon emissions.

The remainder of this paper proceeds as follows. Section 2 briefly reviews the background on corporate taxation and debt tax shield. Section 3 describes the data and presents the empirical results. Section 4 presents our general-equilibrium model and studies the consequences of counterfactual reforms. Section 5 concludes.

2 Background on Corporate Taxation and Debt Tax Shield

Corporate taxation. Firms incorporated under subchapter C of the federal tax code (C corporations) are required to pay taxes at corporation tax rates on their taxable income, which is computed as revenues net of allowable cost deductions.[5] C corporations are also taxed in every state in which they have a physical presence. As for the federal code, most states tax firms on their profits at the state-level corporate tax rate, applied to the state's apportioned share of taxable income. A few states—Nevada, Ohio, Texas, and Washington as of 2021—levy instead a gross receipts tax based upon firms' revenues rather than income. State taxes are deductible expenses for federal income tax purposes. Firms with activities abroad also pay taxes on their profits in foreign countries.

The tax shield of debt. The federal tax code allows C corporations to deduct interest payments from their profits. Instead, dividends paid to shareholders are not deductible. Tax deductibility of interest payments exists in virtually all countries. Some countries introduced an allowance for corporate equity (such as Croatia in 1994, Brazil in 1996, Italy in 1997, Austria in 2000, Belgium in

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[5] Firms incorporated under subchapter S of the federal tax code, as well as unincorporated firms organized as partnerships and sole proprietorships do not pay taxes at the firm level, but instead pass all profits to their owners. Firms included in our sample are all C corporations.

2006 and Portugal in 2010), which consists in granting a similar tax deductibility to equity. Other countries have introduced measures that put a cap on interest deductibility, often called "thin capitalisation rules" or "income stripping rules". For instance, since 2018 large firms in the United States are subject to Section 163(j) of the Internal Revenue Code, which limits interest expense to 30 percent of a corporate group's earnings before interest, taxes, depreciation and amortization (EBITDA).[6]

The tax shield of debt represents a large subsidy to debt financing. Graham (2000); Kemsley and Nissim (2002); Van Binsbergen, Graham, and Yang (2010) calculate the value of the tax benefits of debt finance for the U.S. using different approaches, and find it to be about 10% of firm value. Despite its importance and its popularity, the motivation behind the introduction of a tax advantage for corporate debt is unclear. De Mooij (2012) notes that the original rationale is that interest payments are typically perceived as a cost of doing business, while equity returns are seen as business income. These accounting principles are then reflected into the tax code, which allows interest payments to be deductible for the corporate income tax as a cost, unlike dividends.[7] What is more, from an economic point of view, both interest and equity payments represent a return to capital owners, and it is not obvious why debt should enjoy a subsidy. If anything, to the extent that debt financing is associated with negative externalities (Lorenzoni, 2008), most existing theories suggest that the return on debt should be taxed at a higher rate than the return on equity.[8] In addition, the debt tax shield can encourage debt shifting within multinationals (Huizinga, Laeven, and Nicodeme, 2008). In fact, several policy proposals advocate an elimination of the tax advantage of debt.[9]

Economic effects. The corporate income tax lowers the return on capital and, as a result, depresses investment. In general equilibrium, if two firms are taxed at different rates, the more heavily taxed firm tends to shrink, while the other tends to expand. Even though two firms in the same location typically face similar statutory tax rates, a series of tax deductions can lead to different *effective* tax rates, depending for instance on the type of assets they acquire and the way

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[6] See https://www.oecd.org/tax/beps/corporate-tax-statistics-database.htm for data on interest limitation rules across countries.

[7] For investors, personal taxes on interest payments mitigate the corporate tax advantage of debt, while personal taxes on capital gains and dividends reinforce the tax advantage of debt. In practice, even accounting for personal taxes, debt enjoys a tax advantage.

[8] An exception is the theory developed in He and Matvos (2016) showing that, in a war-of-attrition model, higher debt levels implied by the tax shield of debt increase firms' incentives to exit, which, although costly for the firm, is socially beneficial. More generally, debt financing can generate a positive externality by fostering creative destruction. Differences in tax treatment between debt and equity could also be desirable in the presence of market imperfections, if they mitigate other pre-existing distortions.

[9] For instance CBO (1997), page xi: *Current proposals would improve the coordination of business- and personal-level taxes and would "level the playing field" among different forms of financing and types of capital. The current income tax system favors financing through debt over equity, [...]. Most proposals for fundamental tax reform would remove, or at least substantially alleviate, those tax inequalities. The result would be a more economically efficient allocation of resources. In the short run, costs of capital for incorporated businesses that rely on equity would fall.* See also IMF (2016). From a policy point of view, to the best of our knowledge, our paper is the first to highlight the potential positive consequences for the environment of removing the tax shield of debt.

they finance their activities. In fact, certain types of capital are cheaper to finance with debt than others, hence, a preferential tax treatment for debt introduces an implicit subsidy to some types of capital. In particular, investment in tangible capital (such as machinery and equipment) can sustain higher leverage ratios, and therefore enjoy a lower after-tax cost of capital than investment in intangible capital.

Finally, firms also pay a variety of other taxes, such as payroll taxes, property taxes, sales taxes, environmental taxes, or unemployment insurance contributions. They can also benefit from tax incentives targeted to specific geographical areas or industries,[10] and deductions from non-debt tax shields, such as accelerated depreciation rules on certain type of eligible capital. While these taxes are not the primary focus of our paper, we consider their impact on firms in our empirical and theoretical analysis.

3 Empirical Evidence

3.1 Data

Our empirical analysis uses two main sources of data: firms' financial information from Compustat Northamerica Fundamentals, and firms' carbon emissions from Trucost. In order to measure the weighted average statutory tax rate that U.S. firms face in each year based on the location of their operations, we also use data on the location of firms' headquarters and establishments within the U.S. from Infogroup, the location of U.S. multinationals' activities across countries from Factset, statutory corporate tax rates and apportionment factors across U.S. states, and statutory corporate tax rates across foreign countries from the Tax Foundation. We present these datasets and summary statistics below.

Firm-level financial information. We obtain balance sheet and income statement data for all firms headquartered in the U.S. from Compustat Northamerica Fundamentals Annual for the years 2004-2019. For our purposes, we retrieve information on firms' sales (Compustat item SALE), taxes paid on their profits (Compustat item TXPD), interest payments (Compustat item XINT), operating income (Compustat item EBITDA), debt (the sum of short-term and long-term debt, Compustat item DLC+DLTT), and property, plant, and equipment (Compustat item PPENT). We measure firm age as the difference between the current year and the year founded, using information from Jay Ritter's website. If the year founded is missing, the first year in Compustat is taken instead.

Firm-level carbon emissions. We merge the accounting data to firm-level direct (scope 1) carbon emissions from Trucost using the CUSIP identifier.[11] In our baseline sample we focus on

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[10] In that vein, Metcalf (2018) discusses specific corporate tax deductions in the oil and gas sector.

[11] Firm-level carbon emissions data are assembled by various data providers. All these providers follow the Greenhouse Gas Protocol that sets the standards for measuring corporate emissions. Trucost is the data provider with the broadest coverage, covering more than 15,000 firms and 95% of market capitalization globally (Trucost, 2019). Cor-

firms with non-missing emissions data in Trucost in a given year. As shown in Online Appendix Figure A.1, coverage in Trucost has increased over time. In 2018, we observe carbon emissions for around 70% of Compustat firms, which represent more than 90% of total assets of publicly listed firms. Aggregate emissions in Trucost for Compustat firms equal around 2 gigatonnes of carbon dioxide equivalent in 2018, that is around 40% of total emissions generated by the private sector in the United States. Our main variable of interest is carbon intensity, defined as the ratio of firms' carbon emissions over their sales (expressed in 2019 USD). Due to the different reporting standards for financial institutions, we exclude financial firms (with 2-digit SIC codes 60 to 69). We further restrict the baseline sample to firms with at least 10 mn USD sales.[12]

Firm-level tax rates. We compute $\tau_{f,t}$, the weighted-average statutory tax rate that firm f faces in year t using the following formula:

$$\tau_{f,t} = \omega^{f}_{US,t} \times (\tau_{fed,t} + (1-\tau_{fed,t}) \cdot \sum_{s} \omega^{f,Domestic}_{s,t} \cdot \tau_{s,t}) + (1-\omega^{f}_{US,t}) \times (\sum_{c} \omega^{f,Foreign}_{c,t} \cdot \tau_{c,t}), \quad (1)$$

where $\omega^{f}_{US,t}$ is the share of firm f's domestic sales, $\tau_{fed,t}$ is the U.S. federal tax rate in year t, $\omega^{f,Domestic}_{s,t}$ is the domestic tax weight of firm t in U.S. state s and year t (computed using both information on the distribution of firms' sales and employment across U.S. states and apportionment factors on sales, employment, and property in each U.S. state as described in more detail in Giroud and Rauh (2019))[13], $\omega^{f,Foreign}_{c,t}$ is the tax weight of firm t in foreign country c and year t (computed using information on the distribution of U.S. firms' sales across foreign countries), $\tau_{s,t}$ is the corporate tax rate of U.S. state s in year t, and $\tau_{c,t}$ is the tax rate of foreign country c in year t.[14] We set $\tau_{s,t}$ to 0 for states with a gross receipts tax in year t.[15]

For state-level corporate tax rates, we take the data shared by Giroud and Rauh (2019) and Baker, Sun, and Yannelis (2019). They construct the dataset using information mainly from the Tax Foundation; we extend their data until 2019. We use the data shared by Giroud and Rauh

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relations across data providers are on average 0.99 and 0.98 for reported scope 1 and scope 2 emissions respectively, but considerably lower for estimated data and scope 3 emissions (Busch, Johnson, and Pioch, 2018).

[12] Including firms with sales below 10 million (less than 2% of firms with available data on carbon emissions) would introduce extreme values in the distribution of firms' carbon intensity. Our results are not sensitive to the choice of the cutoff.

[13] Formally, we define the domestic tax weights of U.S. state s in year t for firm f as: $\omega^{f,US}_{s,t} = \alpha^{Sales}_{s,t} \cdot \frac{Sales^{f,US}_{s,t}}{\sum_{s \in US} Sales^{f,US}_{s,t}} + (1-\alpha^{Sales}_{s,t}) \cdot \frac{Emp^{f,US}_{s,t}}{\sum_{s \in US} Emp^{f,US}_{s,t}}$, with $\alpha^{Sales}_{s,t}$ being the apportionment factors on sales in state s and year t, $Sales^{f,US}_{s,t}$ and $Emp^{f,US}_{s,t}$ being respectively total sales and total employment of firm f in state s and year t. This equation implicitly assumes that the distribution of firm employment across U.S. states is a good proxy for the state distribution of both firms' properties and payroll expenses, that we do not observe. Note that the sum $\omega^{f,US}_{s,t}$ across U.S. states is not necessarily equal to 1 because sales apportionment factors are heterogeneous across states. More and more states moved over time from an equally weighted formula – with equal weight on sales, property, and payroll – to a single-sales apportionment rule (i.e., $\alpha^{Sales} = 100$). States generally set the payroll and property apportionment factors equal to each other.

[14] We compute the combined domestic tax rate as $\tau_{fed,t} + (1-\tau_{fed,t}) \times \sum_{s} \omega^{f,US}_{s,t} \cdot \tau_{s,t}$ to account for the deductibility of state taxes for federal income tax purposes.

[15] In these states, interest expenses are not tax-deductible.

(2019) on apportionment factors on sales, property and payroll for each state obtained from the Commerce Clearing House's State Tax Handbooks, that we extend until 2019. We also obtain data on tax rates for each foreign country and year from the Tax Foundation. We use information gathered by Infogroup to identify firms' headquarter state location as well as the employment and sales for each of their domestic establishments. Infogroup contacts establishments by phone and collects data, among other things, on sales and the number of full-time equivalent employees.[16] We use Factset to obtain the distribution of U.S. multinationals' foreign sales across countries.

In the empirical analysis below, we use $\tau_{f,t}$ of Equation 1 to compute the value of the tax shield, that is, the amount of taxes that each firm saves by deducting interest payments to debtholders, defined as:

$$Tax\ Shield_{f,t} = Interest\ Payments_{f,t} \times \tau_{f,t}. \tag{2}$$

For the years 2018 and 2019, to take into account the cap on interest deductibility in the new version of Section 163(j) of the Internal Revenue Code introduced by the Tax Cuts and Jobs Act, we set interest payments equal to 30 percent of EBITDA when higher.

Descriptive statistics. Table 2 shows summary statistics for our sample, which consists of 13,791 Compustat firm-year observations between 2004 and 2019 for which we observe both carbon emissions and financial information. The average firm in our sample emits 0.22 tonnes of carbon per 1 thousand USD sales. The distribution of carbon intensity across firms is skewed, with a median of 0.02 tonnes of carbon and a 99th percentile of 4.6 tonnes of carbon per 1 thousand USD sales. When we compute the statutory tax rate faced by firms in our sample using formula (1), we find an average of around 34%. When we compute the tax shield of debt financing using formula (2), we find that firms enjoyed a tax shield of around 1% of their sales—a sizable amount when compared to the profit taxes that they paid, on average around 2.2% of their sales.

Finally, as shown in the lower panel of Table 2, the average firm in our sample is large, with sales of around 11 bn USD.[17] The average firm is 46 years old, generates around 27% of its sales abroad, has an operating profit margin of around 12%, an average stock of debt (respectively, property, plant and equipment) equivalent to 51% (respectively, 56%) of their sales, and pays an interest rate of around 6.8% on its debt (measured by dividing interest expenses by beginning-of-period debt).

[INSERT TABLE 2]

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[16] In contrast, Compustat records only the current and not the historical location of each firm's headquarter, and does not provide information on the location of a firm's establishments. In our sample, 45% of firms' U.S. employees are located in different states than firms' headquarters.

[17] The average firm in our sample is larger than the average firm in Compustat. This is due to the fact that information on carbon emissions are more likely to be available for the largest firms in the economy.

3.2 Baseline Results on Corporate Taxes and Carbon Emissions

We now turn to the relationship between corporate taxes and carbon intensity. In our baseline specification, we estimate the following OLS regression at the firm-year level from 2004 to 2019:[18]

$$Taxes/Sales_{i,t} = \beta \times Carbon/Sales_{i,t} + \gamma_{s,t} + \epsilon_{i,t}, \tag{3}$$

where $Taxes/Sales_{i,t}$ is the firm-level ratio of taxes over sales, and $Carbon/Sales_{i,t}$ is the ratio of carbon emissions over sales of firm i in year t. $\gamma_{s,t}$ are either year fixed effects of headquarter state-year fixed effects, in which case the correlation between taxes paid by corporations and their carbon emissions is estimated within groups of firms subject to the same statutory corporate tax rate in the state of their headquarter.[19] In some specifications, we also include baseline controls for firm size, firm age, the share of foreign sales, and firm profitability. We cluster standard errors at the 4-digit SIC industry level to account for serial correlation in $\epsilon_{i,t}$ across firms of the same industry.[20]

Note that one can interpret the estimated coefficient β in equation (3) as the implicit carbon tax implied by corporate taxation (or carbon subsidy when $\beta < 0$), expressed in dollars per tonnes of carbon. To clarify this point further, consider the following example with two firms; firm A operates in an emission-intensive industry (say, manufacturing) and emits 1,000 kilo tonnes of carbon to produce goods and generate sales of 1 billion USD; firm B operates in an emission-free industry (say, business services) and generates sales for the same amount. Suppose we were to estimate $\beta = 10$ in equation (3). We would then conclude that firm A in the emission-intensive industry pays more corporate taxes than firm B, that is, the corporate taxation system contains an implicit tax of 10 dollars for each tonne of carbon emitted. Our analysis will not only document the difference in taxes paid by firm A and firm B; in Section 3.4, we will also isolate empirically the firm characteristics that explain the difference in taxes paid between the two firms.

[INSERT TABLE 3]

Panel A of Table 3 presents the results for the relationship between carbon emissions and corporate taxes. Columns (1) to (3) show the relationship in unweighted regressions, whereas columns (4) to (6) present the estimates in regressions weighted by firm size. In columns (2), (3), (5), and (6), we add our baseline controls. Finally, we include state-year fixed effects as a first pass to control for state-level variation in statutory tax rates across firms in columns (3) and (6). The point estimate

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[18] In equation (3), we use taxes as the dependent variable and carbon intensity as the independent variable. As shown below, this allows us to obtain from the coefficient β the dollar subsidy on carbon emissions implied by corporate taxation. Alternatively, one could consider a specification in which carbon intensity is regressed on the profit taxes paid by U.S. corporations. In that vein, we will study the implications of changes in corporate taxation policies on aggregate carbon emissions through a general-equilibrium model in Section 4.

[19] For studies looking at the effect of corporate tax rates on firms' outcomes, see e.g. Heider and Ljungqvist (2015); Ivanov, Pettit, and Whited (2020); Titman and Wessels (1988); Graham (1996); Faccio and Xu (2015).

[20] By clustering standard errors at the industry level, we obtain more conservative t-statistics compared to specifications in which the error term is clustered at the firm level.

for β is similar across specifications, ranging between -4.1 and -6.4, and is always statistically significant at the 1%-level. If anything, the magnitude is larger in weighted specifications. The point estimate is similar when we add controls for firm size, age, the share of foreign sales, and more importantly for firm profitability. This indicates that the negative relationship we uncover in columns (1) and (4) is not driven by differences in profits between clean and dirty firms.[21] What is more, the estimates imply that 1 tonne of carbon emissions is associated with around 5 USD of lower taxes in the cross section of U.S. firms.[22]

Let us emphasize that we do *not* interpret the estimated coefficient $\hat{\beta}$ in equation (3) as the causal impact of carbon emissions on profit taxes. We do not claim, for instance, that firms could save on taxes by using a dirty technology. Instead, we use equation (3) as a descriptive regression that estimates the relationship between carbon intensity and profit taxes paid by U.S. corporations in the cross-section, and use it to recover the dollar value of the carbon subsidy embedded in the current U.S. corporate taxation scheme. In the following section, we investigate the reason for which carbon-intensive firms can pay lower taxes. We show that the negative relationship between carbon intensity and profit taxes is largely explained by differences in the tax shield of debt across U.S. firms.

Tax Shield. As the U.S. tax code allows firms to deduct interest payments from their earnings, differences in taxes paid by clean versus dirty firms can in principle come from differences in firms' profitability, or from differences in the structure of their liabilities.[23] As a first step for understanding why dirty firms to pay lower taxes, we decompose total corporate taxes paid by each firm as the sum of the tax shield generated by debt financing (computed using formula 2), i.e. as interest expenses times $\tau_{f,t}$, the corporate tax rate faced by firm f in year t) and the hypothetical taxes that the firm would have paid were it entirely equity-financed (which are given by total corporate taxes plus interest expenses $\times$ $\tau_{f,t}$). To establish which of the two components drives the correlation with carbon emissions, we estimate our baseline equation (3) separately for each component.

Panel B of Table 3 shows that dirty firms benefit from a larger tax shield of debt, even after controlling for firm size, age, the share of foreign sales, and profitability in column (2), and for firms' headquarters state × year fixed effects in column (3). Estimates range between 4.4 and 4.5, and are statistically significant at the 1%-level. Note also that the estimates have the opposite sign and have virtually the same magnitude as the coefficients in Panel A of Table 3. This indicates that the negative relationship between taxes and emissions presented in Panel A is explained by a

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[21] In our sample, firms with high carbon intensity have slightly higher profit margins. This is why the point estimate for β becomes slightly larger in absolute value once we control for differences in firms' profitability.

[22] To the extent that reported carbon emissions are noisy measures of the true emissions of U.S. corporations, this leads to a standard downward bias in our specifications, and thus these estimates are lower bounds on the true subsidy on carbon emissions implied by corporate taxation.

[23] As noted before, it might also be that dirty firms are more likely to locate their activities in states with lower tax rates. However, as shown in Table 5 below, we fail to find any robust correlation between carbon intensity and the weighted average state corporate tax rates that firms face.

higher tax shield of debt for dirty firms. We confirm this result in columns (4) to (6) of Panel B where we regress the hypothetical taxes that firms would pay if they were financed only with equity on their carbon intensity. The estimated coefficient is small and not statistically significant, which indicates that there is no robust residual relationship between taxes and carbon emissions, beyond the robust relationship between the debt tax shield and carbon emissions that we uncovered in columns (1) to (3).

3.3 Robustness

In this subsection, we conduct a series of empirical checks to test the robustness of our baseline findings.

[INSERT TABLE 4]

Private firms. One limitation of our main sample is that it only includes publicly listed firms. One concern is that the implicit tax subsidy on carbon emissions might be different in the universe of privately held firms. To shed light on this issue, we exploit the fact that Trucost also provides information on carbon emissions for a set of privately-held firms. We merge this data with financial information from Refinitiv and replicate our main specifications in the sample of private firms observed in both Trucost and Refinitiv. We end up with 2,686 observations over the same sample period. As shown in column (1) of Panels A and B of Table 4, the coefficient on carbon emissions is very similar to the one we obtain in our sample of publicly listed firms. This additional analysis suggests that our estimates are likely to be representative for the universe of U.S. private firms.

Domestic firms versus multinationals. One may worry that our results are driven by the fact that multinational firms emit more carbon emissions and at the same time locate their activities in low-tax countries. Although we show below that there is no relationship between firms' carbon emissions and the weighted-average profit tax rates faced by firms, we can run our baseline specifications separately for domestic versus firms with foreign activities in order to test this further. As shown in columns (2) and (3) of Panels A and B of Table 4, our baseline coefficients on both taxes paid and tax shield are virtually the same for domestic and multinationals.

Measurement of carbon emissions. Another concern is that the estimates are biased by the way carbon emissions are reported by firms. If for instance, firms paying more taxes are systematically more likely to under-report their carbon emissions, our specifications would overestimate the true indirect subsidy associated to tax deductibility of debt. While there is no obvious reason for why this should be the case, we run our baseline specifications separately for firms reporting their emissions, and for firms for which carbon emissions are estimated by Trucost, the data provider. As shown in columns (4) and (5) of Panels A and B of Table 4, our baseline coefficients on both taxes paid and tax shield are virtually the same in both subgroups, which strongly mitigates the concern that the measurement of carbon emissions could bias our findings. As an additional test, we utilize the carbon emissions of stationary sources, reported to the EPA under the Greenhouse Gas Reporting Program since 2010. Again we find virtually the same coefficients as in our baseline tests, as shown in column (6) of Panels A and B of Table 4, further mitigating concerns that mismeasurement of carbon emissions biases the results.

Relatedly, we test whether our baseline results go through when one considers broader measures of firms' carbon emissions, including also indirect emissions from consumption of purchased electricity, heat, or steam (scope 2), and other indirect emissions from the production of purchased materials, product use, waste disposal, and outsourced activities (scope 3). As shown in columns (7) and (8) of Panels A and B of Table 4, our baseline coefficients on both taxes paid and tax shield are similar when we consider the sum of scope 1 and scope 2 emissions, or the sum of scope 1, scope 2, and scope 3 emissions.[24]

Marginal tax rates. Next, we use estimates of firms' marginal tax rates —developed by Blouin, Core, and Guay (2010)— instead of statutory tax rates to compute the tax shield and find similar results, as shown in column (9) of Panel B of Table 4.

Yearly estimates and leave-one-industry-out specifications. We also check whether the relationship between carbon emissions and corporate taxes is driven by a specific time period or a specific sector. Online Appendix Figure A.2 reports yearly estimates of cross-sectional regressions of, respectively, corporate taxes over sales (Panel A) and tax shield over sales (Panel B) on firms' carbon intensity. While the yearly estimates on corporate taxes show some variation over time, all estimates are negative and statistically significant in all but one year over the sample period. The estimates for the tax shield are all positive and highly statistically significant. Online Appendix Figure A.3 displays estimates of regressions of, respectively, corporate taxes over sales (Panel A) and tax shield over sales (Panel B) on firms' carbon intensity, over the sample period 2004-2019, in leave-one-industry-out specifications. The coefficient on carbon emissions remains virtually the same in all specifications, indicating that the implicit subsidy to dirty firms is not driven by a specific sector.

Log specifications. Finally, we use the log of the carbon/sales ratio as independent variable to address the concern that the distribution of carbon intensity across firms is right-skewed. As shown in Online Appendix Table A.1, we estimate the coefficient on Log(Carbon/Sales) to be about -1.6, which is consistent with a subsidy of around 7 USD per each tonne of carbon emissions. Thus, log specifications imply a value for the tax subsidy in the same order of magnitude, though slightly larger than the one implied by the estimates in Table 3.[25]

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[24] We prefer using scope 1 emission data in our baseline specifications, since it is the most consistent across data providers (Busch, Johnson, and Pioch, 2018), and keep track of linkages across industries using rich network structures in the model part.

[25] An estimate of -1.6 on Log(Carbon/Sales) indicates that an increase in carbon intensity by 10% is associated with a decrease in taxes by 0.16 USD per thousand of sales. Starting from the average carbon intensity of 0.22 (tonnes per thousand of sales, see Table 2), a 10% increase corresponds to an increase of 0.022 tonnes per 1 thousand of sales. Thus, a 1 tonne increase of carbon emissions is associated with a decrease in taxes of around 7 USD.

Taken together, these robustness checks indicate that there is a robust negative relationship between firms' carbon emissions and the taxes they pay on their profits, and confirm that this relationship is driven by the tax shield of debt.

3.4 The Mechanism

In this section, we shed more light on the mechanism which leads dirty firms to pay lower taxes. We conjecture that firms with substantial emissions—such as energy firms—operate in industries in which the nature of the assets used in production allows them to sustain a higher level of debt and, thus, save on taxes by taking advantage of the tax treatment of debt. We verify this conjecture below where we relate the differential gain from the tax shield to differences in debt levels—and ultimately in asset tangibility—across clean versus dirty firms.

Decomposition of the tax shield. From its definition in formula (2), the higher tax shield enjoyed by carbon-intensive firms could be driven by differences in leverage, cost of debt, or tax rates. In Panel A of Table 5, we thus estimate the relationship between carbon intensity and each of the components of the tax shield separately, i.e., firms' debt-to-sales ratio, firms' interest rate paid on debt (measured as interest expenses over beginning-of-period debt), and firm-level tax rates (computed using formula (1)).

[INSERT TABLE 5]

We find robust evidence that the fiscal advantage of carbon-intensive firms is mostly explained by the higher leverage of such firms. As shown in column (1), there is a positive and strongly statistically significant relationship between carbon intensity and firms' debt-to-sales ratio. In terms of magnitude, 1 tonne of carbon emissions is associated with around 220 USD of higher debt. Multiplying the latter amount by the average cost of debt, 6.8%, and by the average corporate tax rate, 34% (see Table 2), yields a subsidy of 5.1 USD (220 × 0.068 × 0.34) of lower taxes per tonne of carbon—a subsidy of the same magnitude than the estimates presented in Table 3. Panel A of Online Appendix Figure A.4 visualizes the relationship between firms' debt-to-sales ratio and the logarithm of their carbon intensity. Finally, in columns (2) and (3), we fail to find any robust relationship between firms' carbon intensity and, respectively, the cost of debt and firm-level statutory tax rates. We conclude, therefore, that the tax advantage of carbon-intensive firms is due to their higher levels of debt. We are left with the question of what explains the higher leverage of such firms.

Firms' carbon emissions and asset tangibility. We conjecture that differences in debt levels across firms with different carbon-intensity may be driven by differences in asset tangibility. As shown in Panel B of Online Appendix Figure A.4, there is a strong positive relationship between the ratio of property, plant, and equipment over sales and the logarithm of firms' carbon intensity.

We confirm this positive relationship in column (1) of Panel B in Table 5, which is robust to the introduction of state × year fixed effects, and our baseline controls. We then test directly whether tangibility can alone explain the relationships between carbon intensity, firms' leverage, and tax shield that we documented in the previous sections. More specifically, we run the same specifications presented in respectively columns (1) and (3) of, respectively, Table 5, Panel A, and Table 3, Panel B, adding the ratio of property, plant, and equipment (PPE) over sales as an additional control. Strikingly, the coefficient on carbon intensity becomes small and statistically insignificant once PPE over sales is added as an additional control, both in the specification with debt as a dependent variable (column (1) Table 5, Panel A vs column (2) Table 5, Panel B) and in the one with the tax shield as a dependent variable (column (3) Table 3, Panel B vs column (3) Table 5, Panel B). At the same time, the coefficient on PPE over sales is positive and strongly statistically significant.

Decomposing the relationship between PPE and carbon intensity. Next, we ask which type of tangible assets is driving the relationship between PPE and carbon intensity. For this, we rely on Compustat data which provides us with a split of PPE (before substracting accumulated depreciation) into its different components, namely machinery and equipment, buildings, leases, land and improvements, construction in progress, natural resources, and other.[26] Unfortunately, this decomposition is not available for utilities, and is also missing for some firms in other industries. Still, we observe the decomposition for around 60% of firms in our sample. We present the relationship between carbon intensity and each PPE component in Online Appendix Table A.3, with and without control variables. In column (1), we verify that the correlation between total PPE and carbon intensity in the subsample of firms reporting information on the different PPE items is very similar to the one in our main sample (see column (1) of Panel B in Table 5). We then estimate the relationship between carbon intensity and each PPE component. Strikingly, as shown in columns (2)-(7), the relationship between PPE and carbon intensity is almost fully explained by the relationship between Machinery/Equipment and carbon intensity.[27]

Alternative explanations. Differences in the structure of firms' assets are not the only potential explanation for why carbon-intensive firms have higher leverage and benefit from a higher debt tax shield. While we have already shown in Table 5 that the tangibility of firms' assets fully accounts for the relationship between carbon emissions and firm leverage, we can still directly test whether firms' carbon intensity is related to other determinants of firm leverage. In Online Appendix Table A.2, we augment the specifications presented in Panel B of Table 5 with the following variables widely used in the literature on the determinants of firm leverage (see e.g. Faulkender and Smith (2016) for a recent study): growth opportunities as measured by the ratio of research and development expenses to sales, advertising to sales, and the market-to-book ratio, the depreciation-to-assets ratio to capture depreciation tax shields, and whether the firm has a bond rating any month during

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[26] Given that the item natural resources represents a tiny fraction of PPE, we put it together with the category other.

[27] Machinery is also the largest item: it represents on average approximately 60% of PPE, whereas buildings represent around 20% and leases around 13% of PPE.

the fiscal year (in addition to the control variables used in the rest of our paper, namely firm size, firm age, the share of foreign sales, and profitability). As shown in column (2) of Online Appendix Table A.2, adding these variables raises significantly the explanatory power of the econometric model (the R^2 increases from 0.14 to 0.25 compared to the specification without controls presented in column (1)). Still, the coefficient on firms' carbon emissions remains large and highly statistically significant indicating that this set of variables does not explain the relationship between carbon emissions and leverage that we documented above. Instead, when we further add PPE over sales as an additional control in column (3), the coefficient on firms' carbon emissions becomes small and statistically insignificant confirming that differences in asset tangibility is the reason for why carbon-intensive firms have larger leverage. The same patterns emerge in similar specifications with tax shield as the dependent variable, as shown in columns (4) to (6).

Taken together, these findings indicate that differences in asset tangibility across firms with different carbon intensity account for the positive relationship between carbon intensity and leverage, and ultimately for the tax advantage of dirty firms.

Accelerated depreciation and property taxes. To the extent that carbon-intensive firms have more tangible assets on their balance sheets, other provisions in the corporate tax code allowing firms with more tangible assets to pay lower taxes could in principle, as for the tax shield of debt, act as an indirect subsidy in favor of pollution. While a full account of how all the provisions in the corporate tax code benefit or penalize disproportionately more carbon-intensive firms is beyond the scope of this paper (and to a large extent practically unfeasible given the complexity of corporate taxation), we discuss below two other quantitatively important features of the taxation of U.S. corporations which lead to differential tax burdens across firms depending on the nature of their capital: bonus depreciation and property taxes.

Under current bonus depreciation provisions in the U.S., most capital with a class life below twenty years enjoys a 100 percent bonus depreciation, in that firms can immediately deduct the full amount of their capital purchases from their income.[28] Given that investments in machinery and equipment are typically eligible for bonus depreciation, bonus depreciation can also act as an implicit subsidy on carbon-intensive firms.[29] Property taxes paid by corporations represent the

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[28] The Job Creation and Worker Assistance Act of 2002 introduced a 30 percent bonus depreciation for 2002–2003, whose generosity then fluctuated over time. The Tax Cuts and Jobs Act of 2017 raised bonus depreciation to 100 percent for 2018–2022. Beginning on January 1, 2023, bonus depreciation will begin to phase out, and is supposed to disappear in 2027.

[29] Unfortunately, we do not observe the stock of investments eligible to bonus depreciation for publicly listed firms, and therefore cannot easily estimate the implicit dollar subsidy on a ton of carbon emissions associated to bonus depreciation, as we do for the debt tax shield. Still, using data at the industry level from Zwick and Mahon (2017) on z^0, the present discounted value of one dollar of investment deductions before tax using a discount rate of 7% (see Zwick and Mahon (2017) for more details), we can approximate it as the coefficient of a cross-sectional regression of (1-z^0)× investment in machines and equipment (approximated by the annual change in the stock of machines and equipment, before accumulated depreciation, Compustat item FATE) scaled by sales, on carbon intensity in the last years of our sample, when bonus depreciation was raised to 100 percent. 1-z^0 represent the dollar subsidy in present value on 1 dollar of eligible investment (on top of the regular depreciation schedule). We find a subsidy of around 1.7 USD per ton of carbon (significant at the 1 percent level) in a specification with or without control variables for

largest share of total state and local business tax revenue, around 40% in 2019. Given that there is virtually no relationship between carbon intensity and the stock of buildings on firms' balance sheets (see column (3) of Online Appendix Table A.3), we do not expect property taxes to affect disproportionately more carbon-intensive firms.[30]

3.5 Between Versus Within Industry Effects

One natural question is whether the relationship between tangibility, tax shields, taxes and carbon intensity is driven by variation across or within industries. To shed light on this question, we decompose firms' carbon intensity into an industry and a firm-specific component. One challenge in this exercise is that large firms often operate in multiple industries. To overcome this challenge, we utilize information on firms' sales across industries from Compustat Segments data. We first compute the average carbon intensity by SIC4 industry and year across pure play firms operating in only one industry. We then compute for each firm the sales weighted carbon intensity across the different industries it reports in the segments data, *Implied Industry Carbon Intensity*.[31] Finally, we regress the actual firm-level carbon intensity on the carbon intensity implied by the segment data and predict the residuals, *Firm Residual Carbon Intensity*.

Online Appendix Table A.4 shows that both the implied industry carbon intensity as well as the firm residual carbon intensity are associated with higher tangibility, leverage and tax shields and consequently lower taxes, all statistically significant at the 1%-level. As such the effect operates both across and within industries. However, considering the magnitude of the coefficients, the largest part of the overall effect appears to stem from differences across industries. Therefore, our model features heterogeneity in carbon intensity across industries, and for the sake of simplicity abstracts from within-industry variation. One concern in this setting is that clean energy production is also capital intensive. If dirty energy producers rely less on tangible assets than clean energy producers, we would miss an important force in our model pushing in the opposite direction. To address this concern, we rerun our tests within the subsample of energy producers.

We combine carbon emission data from stationary sources from the EPA with data on energy generators submitted to the Energy Information Association (EIA) under form 860, covering all generators at power plants with 1 megawatt or greater of combined nameplate capacity. We aggregate carbon emissions and nameplate capacity of fossil fuel generators (those using coal, petroleum, or natural gas as main energy source) to the firms owning these power plants and restrict the sample to firms operating at least one energy generator in a given year. Panel A of Table A.5 shows that dirtier energy producers (as captured by their carbon intensity) rely more on tangible assets, have

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firm size, firm age, the share of foreign sales, and profitability.

[30] Estimating precisely the relative tax burden at the firm level associated to property taxes is not feasible in practice, as property tax rates vary strongly across local governments, and we do not have information on the precise location of firms' properties (and their eligibility) across the U.S.

[31] We set the implied carbon intensity to the average carbon intensity of the firm's industry in Compustat in case a firm does not appear in the segments data.

higher leverage, enjoy higher tax shields of debt and as a result pay lower taxes. Panel B confirms this finding using instead the fossil fuel energy production capacity as the key explanatory variable. Column (1) shows that indeed firms with more fossil fuel production capacity (scaled by sales) are more carbon intensive. Column (2) then confirms that firms with more fossil fuel production capacity have more tangible assets, more debt, larger tax shields and pay lower taxes. Overall, the evidence shows that the carbon–tangibility–tax shield nexus operates both across and within industries, and importantly holds even within the energy producing sector.

3.6 Economic Significance of the Results

Before moving to the general-equilibrium model and the policy counterfactuals, let us comment on the economic significance of our results by providing a back-of-the-envelope total value of the aggregate subsidy on carbon emissions associated to the U.S. corporate tax system. We use the estimated coefficient $\hat{\beta}$ in Table 3 on the 2018 total carbon emissions of the U.S. corporate sector. We find that the U.S. corporate tax system provided an implicit subsidy to carbon emissions of around 30 USD billion in the year 2018.[32] This amount is of similar magnitude to the USD 33 billion of carbon pricing revenues raised by governments worldwide in 2017 (World Bank, 2018).[33] Our empirical analysis suggests that the corporate tax system can have large quantitative effects on aggregate carbon emissions. In the next section, we present a general-equilibrium model, which we then use to study the impact on production, prices, and carbon emissions of alternative tax policies.

4 The Model

In this section, we build a general-equilibrium model and use it to simulate policy counterfactuals.

Time is discrete and infinite. There is a representative household who consumes, supplies labor elastically and makes portfolio decisions. The economy features N different sectors, indexed by $i \in \mathcal{N} = \{1, ..., N\}$. In each sector, there is a unit measure of firms selling a differentiated good. Goods are sold to final consumers and to other firms, which use them both as intermediate inputs and as investment goods for the production of capital.

The representative household purchases goods from firm f in sector i at price $p^{f}_{i,t}$, and pays a consumption tax τ_c. The household supplies labor for a wage w_t, which is taxed at rate τ_h. The

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[32] 5 USD lower taxes, or higher tax shield, per tonne of carbon implied by our estimates in Table 3 times 6 giga tonnes of carbon equivalent emitted by the U.S. corporate sector in 2018.

[33] Carbon pricing programs cover around 11 giga tonnes of carbon dioxide equivalent or about 20 percent of global GHG emissions. The total value of Emission Trading Schemes (ETS) and carbon taxes reached USD 82 billion in 2018. In the U.S., twelve states that account for around a third of U.S. GDP have active carbon-pricing programs. Those states are California and the eleven Northeast states — Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia — that make up the Regional Greenhouse Gas Initiative (RGGI).

household can save through risk-free government bonds $B_{g,t+1}$, risky corporate bonds $B^f_{i,t+1}$ and equity shares $s^f_{i,t+1}$, for each firm f and sector i. Risk-free bonds pay interest rate r_t. Corporate bonds pay interest rate $r^b_{i,t}$, unless default occurs and the firm is liquidated.[34] Finally, equity trades at price $Q^f_{i,t}$ and entitles the owner to dividends $d^f_{i,t}$, unless default occurs. We describe liquidation and default below, for now we let $\mathcal{L}^f_{i,t}$ and $\mathcal{D}^f_{i,t}$ be the indicator functions of, respectively, the events of liquidation and default for firm f, in sector i, at time t. We assume that interest income is taxed as regular labor income, dividends and capital gains are, instead, taxed at rate τ_d. Finally, the representative household receives lump-sum transfers T_t. All variables are real, the consumption bundle is the numeraire.

The household maximizes

$$\mathbb{E}\sum_{t=0}^{\infty}\beta^t\left(U(C_t)-V(L_t)\right),$$

subject to the budget constraint

$$\begin{aligned}(1+\tau_c)\sum_{i\in\mathcal{N}}\int p^f_{i,t}c^f_{i,t}df &= (1-\tau_h)w_tL_t+T_t+(1+(1-\tau_h)r_{t-1})B_{g,t}-B_{g,t+1}\\ &+\sum_{i\in\mathcal{N}}\int\left\{[1+(1-\tau_h)((1-\mathcal{L}^f_{i,t})r^b_{i,t}-\mathcal{L}^f_{i,t})]B^f_{i,t}-B^f_{i,t+1}\right\}df\\ &+\sum_{i\in\mathcal{N}}\int\left\{[(1-\mathcal{D}^f_{i,t})(1-\tau_d)(d^f_{i,t}+Q^f_{i,t})+\tau_dQ^f_{i,t-1}]s^f_{i,t}-Q^f_{i,t}s^f_{i,t+1}\right\}df,\end{aligned}$$

and a no-Ponzi condition requiring the discounted value of bond holdings to be non-negative in the limit as $t\to\infty$. We assume a nested Dixit-Stiglitz structure:

$$C_t\equiv\prod_{i\in\mathcal{N}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\quad\text{with}\quad c_{i,t}\equiv\left(\int(c^f_{i,t})^{\frac{\sigma_i-1}{\sigma_i}}df\right)^{\frac{\sigma_i}{\sigma_i-1}},$$

and $\sum_i\theta_i=1$, where $\sigma_i>1$ parameterizes the elasticity of substitution within goods in sector i.

Firms within sectors are perfectly symmetric. We can thus solve the problem of the representative firm in each sector and simplify notation by replacing the firm's identifier f. We will refer to the representative firm in sector i as "firm i". In every period, firms choose labor, intermediate inputs, investment, leverage, final-good price and production to maximize the present discounted value of dividends

$$\mathbb{E}\sum_{t=0}^{\infty}\varphi_t d_{i,t},$$

where φ_t is the economy's stochastic discount factor, and expectation is over the event of default, which we describe below.

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[34] To simplify notation, we anticipate that the interest rate will be sector-specific, but not firm-specific; we provide more details when we discuss default.

Capital can be of different types. We index each type with s and let $\mathcal{S}$ denote the set of types. We also let $\mathcal{T}$ and $\mathcal{I}$ denote, respectively, the subsets of $\mathcal{S}$ corresponding to tangible (e.g., structures, equipment) and intangible (e.g., intellectual property) capital.

Output $y_{i,t}$ is produced through a constant-returns-to-scale production function

$$y_{i,t} = \mathcal{F}_i\left(z_i, \{x_{i,j,t}\}_j, \ell_{i,t}, \{k^s_{i,t}\}_s\right), \tag{4}$$

where $x_{i,j,t}$ is intermediate input from sector j, $\ell_{i,t}$ is labor, $k^s_{i,t}$ is the amount of type-s capital owned by the firm, and z_i is sector-specific productivity (which, for simplicity, is assumed to be constant).

Investment. Type-s capital owned by firm i depreciates at rate $\delta^s_i \in (0,1]$. Firms can vary the amount of capital through investment, by combining inputs from different sectors. We allow such combinations of inputs to be sector specific. Formally, capital of type s in sector i follows the law of motion:

$$k^s_{i,t+1} = (1-\delta^s_i)k^s_{i,t} + I^s_{i,t},$$

where investment $I^s_{i,t}$ is a composite of different inputs $I^s_{i,t} \equiv \prod_j (i^s_{i,j,t}/\omega^s_{ij})^{\omega^s_{ij}}$, $\omega^s_{ij} \in [0,1]$, $\sum_j \omega_{ij} = 1$. We let $q^s_{i,t}$ denote the price of capital of type s, in sector i, at time t. Firms also trade capital in a secondary market, which we describe below.

Default. Each firm is subject to an idiosyncratic default shock. We assume process for default that is tractable and yet delivers a rich set of implications for interest rates, equity returns and leverage. We will use this flexible specification to match the empirical evidence. More specifically, the default process implies that in equilibrium both the interest rate on corporate debt and leverage will be sector specific, and will depend on the amount of tangible capital owned by the firm. The positive relationship between leverage and asset tangibility is consistent with the empirical evidence of Section 3.4.

To maintain tractability, we assume that both default and liquidation shocks are exogenous. More specifically, at the beginning of every period, before production takes place, a firm can be hit by an idiosyncratic default shock with probability $(\rho_i + \lambda_i)$, with ρ_i, $\lambda_i > 0$ and $\rho_i + \lambda_i < 1$. When default occurs, firm's equity becomes worthless. There are two types of default: restructuring and liquidation. Conditional on default, with probability $\rho_i/(\lambda_i + \rho_i)$ the firm must be restructured to continue production. A firm that undergoes restructuring keeps a sector-specific and capital-specific share $\psi_{i,s}$ of its assets; the remaining capital is seized and transferred lump-sum to households. The assets retained by the firm are sold in the secondary market to repay bondholders. A restructured firm can issue new debt and equity, and restart production.

All firms in default that cannot be restructured must be liquidated. Thus, with probability $\lambda_i/(\lambda_i + \rho_i)$ a firm in default is liquidated. Firms in liquidation lose all their assets (which are transferred lump-sum to households) and exit the economy permanently. To keep the total mass of firms unchanged, we assume that liquidated firms are immediately replaced with new firms with the same technology.

Finally, we assume the existence of a secondary market where households can sell the assets that were transferred to them to restructured and newly-born firms.

Leverage. Since firms in liquidation lose all of their assets, firms in our model cannot issue risk-free debt. More specifically, lenders can recover up to a fraction $\psi_{i,s}$ of type-s assets from firm i, unless the firm is liquidated. Debt is thus risky and will command a credit premium in equilibrium, i.e., $r^b_{i,t+1} > r_t$. Finally, note that any borrowing above the aforementioned debt threshold will not be repaid, even if the firm is restructured. We treat this additional borrowing as equity and assume that it does not enjoy a tax shield. Formally, we require debt $b_{i,t+1}$ to be such that

$$b_{i,t+1} \leq \frac{1}{1+r^b_{i,t+1}} \sum_{s \in \mathcal{S}} \psi_{i,s} q^s_{i,t+1} k^s_{i,t+1}. \tag{5}$$

In equilibrium, the interest rates on risk-free and risky debt as well as the equity return will be a function of taxes and default probabilities. Our default process implies that the probabilities of restructuring and liquidation are independent of the quantity of debt. Below we make an assumption on model parameters ensuring that equity is more expensive than debt, consistent with empirical evidence. Together, these assumptions simplify the leverage decision as it implies that it is always optimal to issue as much as debt as possible. Formally, condition (5) will hold with equality. As a result, firms with more tangible capital will tend to have a higher leverage, consistent with the empirical literature (see e.g. Rajan and Zingales (1995)) and the evidence in Table 5.[35]

Dividends. Firms pay profit taxes on their taxable income. The U.S. tax code allows firms to deduct expenditures on intermediate inputs, labor compensation, capital depreciation and interest. Firms can also deduct R&D expenses, which we interpret as investment in intangible capital. Finally, firms must pay a property tax on existing capital. Formally, taxable income and dividends equal, respectively,

$$\Pi_{i,t} = p_{i,t} y_{i,t} - \sum_{j \in \mathcal{N}} p_{j,t} x_{i,j,t} - w_t \ell_{i,t} - \sum_{s \in \mathcal{T}} \delta^s_i q^s_{i,t} k^s_{i,t} - \sum_{s \in \mathcal{I}} q^s_{i,t} I^s_{i,t} - \sum_{s \in \mathcal{S}} \tau^s_k q^s_{i,t} k^s_{i,t} - r^b_{i,t} b_{i,t}$$

and

$$d_{i,t} = (1-\tau_p)\Pi_{i,t} - \sum_{s \in \mathcal{T}} q^s_{i,t}(k^s_{i,t+1} - k^s_{i,t}) + b_{i,t+1} - b_{i,t},$$

where τ_p is the profit tax and τ^s_k is the capital tax on type-s capital (e.g., a property tax on non-residential buildings).

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[35] The default process implies that leverage increases in the share of tangible assets. Corporate rates, instead, are independent of such assets and, as a result, do not depend on firm's characteristics. It is straightforward to generalize the default process to make both the amount of borrowing and the cost of debt depend on tangible capital: all is needed is to assume that lenders can recover a fraction of tangible capital even if the firm is liquidated.

Emissions. We assume that production generates emissions as a byproduct. More specifically, firm i's carbon emissions are $E_{i,t} \equiv e_i y_{i,t}$, where e_i is the emission rate. Total emissions in the economy are thus $E_t = \sum_i E_{i,t}$. Note that the emission rate is assumed to be a constant, thus, policy changes affect emissions only insofar as they vary production. In a more general setting, firms would be able to react to policy by investing in cleaner technologies. This innovation channel is complementary to the one considered in this paper; we abstract from it to keep the analysis simple.

Government and equilibrium definition. In every period, the government collects taxes, issues risk-free bonds $B_{g,t+1}$ and sets lump-sum taxes to satisfy the budget constraint

$$TR_t + B_{g,t+1} = (1 + r_{t-1})B_{g,t} + T_t, \tag{6}$$

where TR_t is tax revenues.[36]

An equilibrium is a collection of household and firm decisions, prices and government policies (i.e., tax rates, bond issuance, and lump-sum transfers) such that every agent optimizes, the government budget constraint is satisfied, and markets clear. In particular, the goods-market in each sector and the aggregate labor market must clear:

$$y_{i,t} = c_{i,t} + \sum_{j \in \mathcal{N}} x_{j,i,t} + \sum_{s \in \mathcal{S}} \sum_{j \in \mathcal{N}} i^s_{j,i,t} \quad \text{and} \quad L_t = \sum_{i \in \mathcal{N}} \ell_{i,t}. \tag{7}$$

In addition, the market for risk-free bonds, corporate bonds, equity and used capital in each sector must all clear.

4.1 Model Solution

Let's start with the household problem. At the optimum, consumption of the good produced by sector i satisfies

$$p_{i,t} c_{i,t} = \theta_i P_t C_t, \tag{8}$$

where $P_t \equiv \prod_i p_{i,t}^{\theta_i}$ is the price of the consumption basket, which we normalize to 1. Optimal choice of labor, L_t, satisfies the intra-temporal condition:

$$\frac{V'(L_t)}{U'(C_t)} = \frac{1 - \tau_h}{1 + \tau_c} w_t. \tag{9}$$

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[36] Formally, $TR_t \equiv \tau_c \sum_i p_{i,t} c_{i,t} + \tau_h w_t L_t + \tau_h r_{t-1} B_{g,t} + \sum_i \{TP_{i,t} + \tau_p \Pi_{i,t} + \sum_s \tau^s_k q^s_{i,t} k^s_{i,t}\}$, where $TP_{i,t}$ denotes tax revenues from portfolio investment in sector i: $TP_{i,t} = \tau_h (1 - \lambda_i) r^b_{i,t} b_{i,t} + \tau_d [(1 - \rho_i - \lambda_i)(d_{i,t} + Q_{i,t}) - Q_{i,t-1}]$; and where we have used the fact that in every period a mass λ_i of firms in sector i is liquidated and a mass $(\rho_i + \lambda_i)$ is in default.

Finally, we consider the portfolio problem. From the choice of risk-free bonds we obtain the Euler equation:

$$U'(C_t) = \beta(1 + (1 - \tau_h)r_t)U'(C_{t+1}).$$

In addition, optimal choices of corporate bonds and equity deliver two asset-pricing conditions for, respectively, corporate-bond rates and equity returns:

$$r^b_{i,t+1} = \frac{\lambda_i + r_t}{1 - \lambda_i} \tag{10}$$

and

$$r^e_{i,t+1} \equiv \frac{d_{i,t+1} + Q_{i,t+1}}{Q_{i,t}} - 1 = \frac{(1 - \tau_d)(\rho_i + \lambda_i) + (1 - \tau_h)r_t}{(1 - \tau_d)(1 - \rho_i - \lambda_i)}. \tag{11}$$

Remember that $r^b_{i,t+1}$ represents the ex-post compensation for holders of risky debt, *conditional* on the firm not being liquidated at time t. Similarly, $r^e_{i,t+1}$ represent the ex-post equity return, conditional on no default. Since there is no aggregate risk, the expected (i.e., unconditional) net compensation to investors, both for risky debt and for equity, must be equal to the net interest rate on risk-free debt. In what follows, we assume that $r^e_{i,t} \geq r^b_{i,t}$ for all industries. This assumption essentially requires ρ_i (i.e., the probability of restructuring) to be sufficiently high relative to λ_i (i.e., the probability of liquidation). Also, it is immediately satisfied if $\tau_d = \tau_h$.

Finally, the household problem implies that the equilibrium stochastic discount factor is $\varphi_t = (1 - \tau_d)^{t+1}/\Pi_{j=0}^{t-1}(1 - \tau_d + (1 - \tau_h)r_{t+j})$.[37] Note that, since aggregate risk is absent, future dividends are discounted with the risk-free interest rate adjusted for taxes.

We now turn to the firm's problem. To derive closed-form expressions, we assume a Cobb-Douglas production function; we will use a CES production function in the robustness analysis below. Formally,

$$\mathcal{F}_i\left(z_i, \{x_{i,j,t}\}_j, \ell_{i,t}, \{k^s_{i,t}\}_s\right) = z_i\zeta_i\Big(\prod_{j\in\mathcal{N}} x^{\alpha_{ij}}_{i,j,t}\Big)^{1-\gamma_i}\Big(\ell^{\phi^\ell_i}_{i,t}\prod_{s\in\mathcal{S}}\left(k^s_{i,t}\right)^{\phi^s_i}\Big)^{\gamma_i}, \tag{12}$$

with $\gamma_i, \phi^\ell_i, \phi^s_i, \alpha_{ij} \in [0, 1]$, and ζ_i is a constant that simplifies expressions below.[38] Constant returns to scale requires $\phi^\ell_i + \sum_s \phi^s_i = 1$ and $\sum_j \alpha_{ij} = 1$.

The optimal choices of labor and intermediate goods are static and satisfy the first-order conditions

$$\mu_i\phi^\ell_i\gamma_i = \frac{w_t\ell_{i,t}}{p_{i,t}y_{i,t}}, \qquad \mu_i\alpha_{ij}(1 - \gamma_i) = \frac{p_{j,t}x_{i,j,t}}{p_{i,t}y_{i,t}}, \tag{13}$$

respectively, where $\mu_i \equiv (\sigma_i - 1)/\sigma_i$ is the inverse of the mark-up. Conditional on total investment

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[37] We use the convention $\Pi_{j=0}^{-1}(1 - \tau_d + (1 - \tau_h)r_j) = 1$.

[38] $\zeta_i \equiv (\gamma_i\phi^\ell_i)^{-\gamma_i\phi^\ell_i}\prod_j((1 - \gamma_i)\alpha_{ij})^{-(1-\gamma_i)\alpha_{ij}}\prod_s(\gamma_i\phi^s_i)^{-\gamma_i\phi^s_i}$.

$I^s_{i,t}$, the optimal choice of $i^s_{i,j,t}$ is also static and satisfies

$$i^s_{i,j,t} = \frac{1}{p_{j,t}} \omega^s_{ij} q^s_{i,t} I^s_{i,t}, \tag{14}$$

where the price of capital is given by $q^s_{i,t} \equiv \prod_j (p_{j,t})^{\omega^s_{ij}}$.

The only dynamic choice is the one about investment $I^s_{i,t}$. The optimal level of tangible capital (i.e., capital of type $s \in \mathcal{T}$) satisfies:

$$\mu_i \gamma_i \phi^s_i = R^s_{i,t} \frac{q^s_{i,t} k^s_{i,t}}{p_{i,t} y_{i,t}},$$

where the rental rate $R^s_{i,t}$ of type-s capital is defined as

$$R^s_{i,t} \equiv \delta^s_i + \tau^s_k + r^b_{i,t} \frac{\psi_{i,s}}{1 + r^b_{i,t}} + \frac{1}{1 - \tau_p} r^e_{i,t} \Big(1 - \frac{\psi_{i,s}}{1 + r^b_{i,t}}\Big) + \frac{1}{1 - \tau_p} (1 + r^e_{i,t}) \Big(\frac{q^s_{i,t-1}}{q^s_{i,t}} - 1\Big). \tag{15}$$

The expression for intangible capital is analogous.

Equation (15) represents the user cost of type-s capital for the firm. It is the sum of depreciation, the tax on capital, and the financing cost that the firm must incur to purchase capital, taking into account the optimal mix of debt and equity. The last term captures the fact that the cost of using capital increases if the price of capital decreases over time. Finally, notice that the factor $1/(1 - \tau_p)$ multiplies only the terms associated to equity (i.e., the last two terms). This is due to the tax shield of debt. It follows that, all other things equal, the user cost falls if firms can finance a higher fraction of their capital with debt.

4.2 A Closer Look at the Mechanism

We can use the model to shed light on the exact mechanism linking corporate taxes to carbon emissions. From our empirical analysis we know that the tax shield of debt is the main determinant of the tax advantage enjoyed by polluting firms. It is then natural to start with a policy that removes the special treatment of debt—this also is the first policy we consider in our counterfactuals below. We begin with the rental rate of capital (15), which in steady state reduces to (we drop the time subscript to denote steady-state variables)

$$R^s_i = \delta^s_i + \tau^s_k + r^b_i \frac{\psi_{i,s}}{1 + r^b_i} + \frac{1}{1 - \tau_p} r^e_i \Big(1 - \frac{\psi_{i,s}}{1 + r^b_i}\Big), \tag{16}$$

for $s \in \mathcal{T}$. If the tax shield was removed, the term related to the cost of debt in (16) would be multiplied by the factor $1/(1 - \tau_p)$—exactly like the equity term. As a result, the rental rate would increase by $\Delta R^s_i = \tau_p/(1 - \tau_p) r^b_i \psi_{i,s}/(1 + r^b_i)$. Notice that the change is proportional to $\psi_{i,s}$—the collateral value of type-s capital. Therefore, although the no-tax-shield policy affects both tangible and intangible capital, it is more pronounced for the former due to its more effective use as collateral.

Firms respond to a change in the rental rate by raising their prices; as a result, production decreases and so do emissions. In fact, up to a first-order approximation, we can derive a sharp characterization for the partial-equilibrium response of the model. This characterization is quite general; in particular, it does not require that the production function takes a specific functional form, only that it exhibits constant returns to scale.

We focus on a single firm (hence, we bring back the firm's identifier) and keep all other prices (investment price, wage, etc.) constant. We can then express the percentage change in the firm's emissions as follows:

$$d\log E_i^f = \frac{d\log \mathcal{D}_i^f}{d\log p_i^f} \times \sum_{s\in\mathcal{S}} \frac{d\log \mathcal{MC}_i^f}{dR_i^s} \times \Delta R_i^s. \tag{17}$$

The first term is simply the price elasticity of demand faced by firm f in sector i. In our Dixit-Stiglitz environment it equals σ_i, i.e., the elasticity of substitution across goods within the sector. The second term is the semi-elasticity of the firm's marginal cost to a change in the rental rate of type-s capital. In Online Appendix B.1, we show that this term is proportional to the firm's holdings of type-s capital scaled by firm's sales, that is, $d\log \mathcal{MC}_i^f/dR_i^s \propto q_i^s k_i^{f,s}/p_i^f y_i^f$.

To sum up, when the tax shield is removed, firms holding more capital—and, in particular, more *tangible* capital—experience a larger increase in their production costs, charge a higher price, and cut production more than firms with less capital. Lower output implies fewer emissions. Finally, notice that equation (17) is the theoretical counterpart of the specification estimated in Table 5 in our empirical analysis. In particular, the model predicts that emissions should be a function of assets (PPE in the empirical analysis) scaled by firms' sales.

An equivalent representation. The model also allows us to formalize the claim that corporate income taxes contain an implicit subsidy to carbon emissions. To do this, we first derive the analogue of (17) for a carbon tax, i.e., a tax τ_e that is proportional to firm's emissions.[39] In Online Appendix B.1, we show that the percentage change in a firm's emissions (in steady state and partial equilibrium) following the introduction of a carbon tax is approximately

$$d\log E_i^f = \frac{d\log \mathcal{D}_i^f}{d\log p_i^f} \times \frac{d\log \mathcal{MC}_i^f}{d\tau_e} \times \tau_e. \tag{18}$$

The first term is exactly the same as in equation (17). The second term captures the change in the firm's marginal cost due to the carbon tax, and it is proportional to the firm's emissions scaled by sales, that is, $d\log \mathcal{MC}_f/d\tau_e \propto E_i^f/p_i^f y_i^f$. Not surprisingly, firms with higher emissions are hurt more by the carbon tax.

The two decompositions (17) and (18) suggest that the no-tax-shield policy can be re-interpreted

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[39] Formally, a firm with emissions $E_{i,t}$ must pay $\tau_e E_{i,t}$.

in terms of a carbon tax. To see this, let $TS_i^f \equiv \tau_p r_i^b b_i^f$ be the model counterpart of the tax shield, and note that we can always find a constant β and a variable ϵ_i^f such that

$$\frac{TS_i^f}{p_i^f y_i^f} = \beta \times \frac{E_i^f}{p_i^f y_i^f} + \epsilon_i^f, \tag{19}$$

where the "error term" ϵ_i^f is orthogonal to the right-hand-side variable. Equation (19) is simply the OLS regression of tax shield on emissions (both of them scaled by firm's sales). From the empirical analysis, we know that carbon-intensive firms enjoy a larger tax shield, thus, $\beta > 0$.

Since $d \log \mathcal{MC}_f / d\tau_e$ in equation (18) is proportional to $E_i^f / p_i^f y_i^f$, in the online appendix we show that the tax shield can be re-interpreted as a combination of a *negative* carbon tax—a subsidy to carbon emissions—and a firm-specific *revenue* tax—i.e., a tax that is proportional to firm's revenues $p_i^f y_i^f$ and equal to ϵ_i^f.[40]

Let us conclude by emphasizing that, as it was also the case for the no-tax-shield policy, condition (19) provides a theoretical justification for our empirical analysis. In fact, one can read the analysis in Section 3.2—where tax shield (scaled by sales) is regressed on emissions (scaled by sales)—as the empirical counterpart of condition (19).

4.3 Calibration

We focus on the corporate sector, excluding government and housing. We have a total of 56 sectors (see Table A.6 in the online appendix for the complete list). We consider exports as final consumption and assume that all output is produced domestically. To study counterfactuals we employ the "exact hat algebra" (Dekle, Eaton, and Kortum, 2008; Costinot and Rodríguez-Clare, 2014), that is, we express equilibrium relations in terms of variations from the baseline equilibrium. For example, letting $X_{i,t}$ and $X'_{i,t}$ denote a variable before and after the policy change, respectively, we write equilibrium relations in terms of the proportional change $\hat{X}_{i,t} \equiv X'_{i,t}/X_{i,t}$.

We let $U(C) = C^{1-\sigma}/(1-\sigma)$ and $V(L) = L^{1+1/\epsilon}/(1+1/\epsilon)$. Here, σ and ϵ parameterize, respectively, the strength of income effect on labor supply and the Frisch elasticity of labor supply. We set $\sigma = 1.7$ (Boppart and Krusell, 2020) and $\epsilon = 0.5$ (Chetty, 2012). We also set $\beta = 0.99$ to target a risk-free real interest rate in steady state of about 1%.

To calibrate the remaining parameters, we combine several datasets. First, from the BEA Input-Output database we obtain yearly data, for the period 1997-2018, on (i) the use of commodities both by industries (as intermediate inputs) and by final users (as personal consumption and investment), and (ii) the value added and its composition by industry. Second, from the BEA Fixed Assets database we obtain data on (i) fixed assets owned by firms and asset-specific depreciation rates, and (ii) the aggregate price of capital goods. Third, from Compustat North America, we obtain

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[40] In the online appendix, we formalize this argument by showing that the two policies (i.e., the no-tax-shield policy and the combination of a carbon tax and a revenue tax just described) have identical effects on carbon emissions up to a first-order approximation.

sector-specific data on corporate debt, corporate rates and total assets for the period 1997-2018. Finally, data on carbon emissions, for the year 2016, is from Trucost, as described in Section 3.1.

The Cobb-Douglas specification implies that, at the optimum, θ_i will coincide with the share in consumption of sector i. Similarly, γ_i is related to the value added share of sector i (it does not coincide with it because of the mark-up), while ϕ_i^ℓ, ϕ_i^s and α_{ij} are obtained from, respectively, the labor share, the type-s capital share, and the intermediate-input share in value added. To calibrate the investment-network parameters ω_{ij}, we follow the methodology proposed in vom Lehn and Winberry (2021).[41] We use sector-level data on 31 different types of assets (25 different types of equipment, 2 types of non-residential structures, and 4 types of intellectual property assets). We extend vom Lehn and Winberry (2021) and construct three different investment networks: one for equipment, one for non-residential structures, and one for intangible assets. Figure A.5 in the online appendix provides a graphical representation of the intermediates and investment networks.

The parameters governing leverage, interest rates and rental rates of capital are of special interest. We use financial data from Compustat to calibrate leverage—defined as the sector-specific ratio of long-term debt over assets—and corporate rates—defined as the sector-specific ratio of total interest payments over long-term debt. We let $\psi_{i,s} = a_i^\psi + b^\psi$ for tangible capital and $\psi_{i,s} = a_i^\psi$ for intangible capital. We then use condition (5), which holds with equality, to estimate these parameters. More specifically, we regress leverage on firms' total holdings of structures and equipment (scaled by total assets) and obtain $b^\psi = 0.43$. We finally set a_i^ψ equal to the regression residuals.

We compute rental rates using (15). In particular, for each of the 31 types of assets, we use data on price of different types of capital, depreciation rates (adjusted to account for trends in capital price), tax rates, interest rates, equity returns, and leverage. Karabarbounis and Neiman (2019) uses a similar expression to estimate rental rates. Relative to their analysis, we allow rental rates to vary with the type of capital and with the firm's sector. In addition, our formula separately accounts for interest expenses—which are shielded from the profit tax—and equity payouts—which are subject to the profit tax. Once we obtain rental rates, we calibrate (sector-specific) mark-ups by using the condition that value added must equal total payments to labor, capital and profits.

Finally, we take tax rates from McGrattan (2020) and set $\tau_c = 0.074$ for the consumption tax, $\tau_h = 0.22$ for the labor income tax (which also equals the tax on interest income), $\tau_d = 0.22$ for the tax on dividends and capital gains, $\tau_p = 0.25$ for the profit tax, $\tau_k^s = 0.003$ for the property tax on non-residential structures (and set $\tau_k^s = 0$ for all other types of capital).

4.4 Policy Counterfactuals

An economy without the tax shield. In our first counterfactual experiment we simply remove the tax shield on debt. More precisely, we simulate an economy in which firms cannot deduct interest

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[41] We are grateful to the authors for kindly sharing their data and providing detailed information on their methodology.

expenses on corporate debt, and compare its steady state to the one of the original economy with the tax shield.

Once the tax shield is removed, aggregate output and consumption in steady state fall by 2.12% and 1.66%, respectively. This change is brought about mostly by a reduction in steady-state capital; the variation in aggregate labor is, instead, very small (0.22%). The fall in output is accompanied by a much larger reduction in total emissions (−5.37%), which suggests that the reduction in output is not uniform across sectors.

[INSERT FIGURE 2]

Panel A of Figure 2 confirms the differential response across sectors. The bars plot the total change in output and the breakdown into different inputs for the six most carbon-intensive sectors, which account roughly for 85% of total emissions. We focus only on these sectors to make the figure more readable; the behavior of the remaining sectors is analogous. The figure shows that firms react to the policy by reducing their inputs and, hence, their output. What is more, the biggest response comes from tangible capital and intermediates; in fact, the variation in labor and intangible capital is negligible.

The fact that aggregate emissions fall more than output suggests that the policy impact is not uniform across sectors. In fact, since we assumed emissions of a sector to be proportional to the sector's output, the larger fall in emissions must come from a reallocation of inputs from carbon-intensive sectors to greener ones. Formally, the total fall in emissions depends on the *correlation* between changes in production and carbon intensity across sectors. This correlation is positive in the model for two reasons—both of which are consistent with the empirical evidence presented in Section 3.4. First, firms in carbon-intensive sectors tend to own more tangible capital. Second, tangible capital allows firms to sustain a higher leverage and, thus, pay relatively lower taxes due to the fiscal advantage of debt.

A budget-neutral policy. In the previous counterfactual we abstracted from government budget. This is without consequence when, like in our model, the government has access to lump-sum taxes. When instead only distortionary taxes are available, government's effort to restore budget balance might imply a further impact on emissions. In this section, we consider an alternative policy reform in which the tax-shield removal is accompanied with the change of another tax, one that keeps either government budget unchanged or aggregate output unchanged. There are several taxes that we can use for this purpose, however, the analysis in the previous section suggests the revenue tax as the ideal candidate.

Although it is not a widely-used tax, a revenue tax has two advantages. First and most importantly, it does not distort input choices. More specifically, while a revenue tax forces firms to cut production, it does so without altering the optimal input mix. Since the key message of the paper is that the tax shield favors capital-intensive firms, a tax that leaves the input mix unchanged is,

		ρ		σ		b^{ψ}	
	baseline	0.8	0.6	1	2	0.30	0.50
emissions	-5.37%	-4.69%	-4.01%	-5.73%	-5.25%	-4.45%	-5.88%
GDP	-2.12%	-2.04%	-2.03%	-2.51%	-2.00%	-1.78%	-2.32%

Table 1. Changes in total carbon emissions and GDP under alternative functional forms and parameters. The baseline calibration corresponds to $\rho = 1$ (and $\varsigma = 1$), $\sigma = 1.7$, $b^{\psi} = 0.43$.

indeed, ideal. Second, the analysis in the previous section suggests that a revenue tax is intimately connected to the tax shield and to the popular carbon tax.

Panel B of Figure 2 illustrates the counterfactual economy with the two aforementioned policies. To understand the figure, consider first the point on the horizontal axis corresponding to a zero tax. This is exactly the case studied in our first counterfactual. The figure also shows that the removal of the tax shield produces a surplus in government budget.

Consider now a movement along the horizontal axis to the left of the zero point. These are values for which the revenue tax is actually a *subsidy*. As we move to the left, firms increase production, thus, GDP increases and so do carbon emissions. In addition, the subsidy is costly for the government, hence, the budget falls. Two points on the graph deserve special attention. The first one is where the government-budget line crosses zero, that is, where the policy mix is budget-neutral. The second one is where the GDP line crosses zero, that is, where the economy produces the same GDP as in the status quo. Importantly, emissions fall in both of these cases. More precisely, the figure suggests that a properly designed policy reform can achieve a fall in total emissions of about 2.39% without any noticeable change in government budget or GDP.

4.5 Extensions and Robustness

In this section, we consider an extended setting in which it is harder for consumers and firms to substitute energy. We also discuss the robustness of our results to alternative parameter values.

CES. So far, we have worked with a Cobb-Douglas function for both the production function and the household's cross-industry consumption aggregator, which implies a unitary elasticity of substitution across inputs and consumption goods. This choice is justified given our focus on steady states. For example, Hassler, Krusell, and Olovsson (2021) argues that, even if substitution between fossil energy and other inputs is low, endogenous innovation in energy-saving technologies implies a constant income share of fossil fuel in the long-run—a property that is consistent with the empirical evidence. Income shares are, indeed, constant in the Cobb-Douglas setting.

To explore the implications of a lower substitution elasticity, we generalize the baseline setting in two ways. First, we assume the following CES aggregator for consumption:

$$C_t \equiv \left((1-\eta)\left(\prod_{i\neq \bar{j}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\right)^{\frac{\rho-1}{\rho}} + \eta(c_{\bar{j},t})^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}},$$

where $\bar{j}$ is the index of the energy sector, η is the share of good $\bar{j}$ in total consumption, θ_i is the share of good $j \neq \bar{j}$ in total consumption from all sectors except $\bar{j}$, and ρ is the elasticity of substitution between any good $j \neq \bar{j}$ and good $\bar{j}$. The definition of $c_{i,t}$ is unchanged. Similarly, we replace the production function (12) with

$$\mathcal{F}_i\Big(\{\hat{x}_{i,j,t}\}_j, \hat{\ell}_{i,t}, \{\hat{k}^s_{i,t}\}_s\Big) = \left(\gamma_i \widehat{VA}_{i,t}^{\frac{\varsigma-1}{\varsigma}} + (1-\gamma_i)\hat{X}_{i,t}^{\frac{\varsigma-1}{\varsigma}}\right)^{\frac{\varsigma}{\varsigma-1}}, \tag{20}$$

where

$$\hat{X}_{i,t} \equiv \left((1-\eta_i)\left(\prod_{j\neq\bar{j}}\hat{x}_{i,j,t}^{\alpha_{ij}}\right)^{\frac{\rho-1}{\rho}} + \eta_i \hat{x}_{i,\bar{j},t}^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}} \quad \text{and} \quad \widehat{VA}_{i,t} \equiv \hat{\ell}_{i,t}^{\phi_i^\ell}\prod_{s\in\mathcal{S}}(\hat{k}^s_{i,t})^{\phi_i^s}.$$

The parameter ς is the elasticity of substitution between the intermediate inputs bundle and the value added bundle; ρ is the elasticity of substitution between energy and all other inputs (for simplicity we assume this elasticity and the household's one to be the same); γ_i and η_i control, respectively, the value added share in production and the energy share in total inputs. Note that for convenience we are defining the production function directly in terms of deviations from a baseline equilibrium (hence, the "hat" notation).

Table 1 contains the numerical results; all derivations are in Online Appendix B.2. We choose $\bar{j} = 4$, which corresponds to the "Utilities" sector.[42] As ρ falls, the economy moves away from Cobb-Douglas and the impact of removing the tax shield on emissions and output becomes more muted. What is more, as ρ becomes smaller the *ratio* between the change in emissions and the change in GDP declines—to generate a given fall in emissions, society must renounce a larger share of income. Since this ratio is constant by construction at the sectoral level,[43] the worse trade-off between income and emissions must be due to a less effective reallocation of inputs from the more polluting sectors to the cleaner ones. This result is intuitive, a smaller value for ρ limits firms and consumers' ability to substitute away from the energy sector, which is both more carbon-intensive and more dependent on the tax shield.

Alternative parameter values. The last columns of Table 1 report the changes in emissions and GDP associated to the no-tax-shield policy for different parameter values. We consider two parameters. First, the income elasticity of labor supply σ. In our baseline calibration we have set $\sigma = 1.7$ following Boppart and Krusell (2020), which derives the necessary restrictions on preference

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[42] Results are robust to the choice of $\bar{j}$. In fact, if we set instead $\bar{j} = 3$ (i.e., the "Oil and gas extraction, mining, and support activities for mining" sector), the drop in GDP is indistinguishable from the Cobb-Douglas case, and the drop in emissions is very close to it.

[43] Sectoral emissions are assumed to be proportional to output, which is in turn proportional to sectoral GDP.

parameters to capture the long-run downward trend in hours worked per worker experienced by most advanced countries. An alternative choice is $\sigma = 1$, which corresponds to logarithmic preferences in consumption and implies, instead, a constant path for hours. For completeness, we also consider a higher value ($\sigma = 2$). Table 1 shows that the fall in emissions and GDP is more pronounced when σ is smaller. To gain intuition, remember that the no-tax-shield policy reduces income because it makes capital (in particular, tangible capital) more expensive. Households respond by supplying more labor—this response being stronger for higher σ—which in turn makes it cheaper for firms to substitute away from capital and, therefore, to buffer the fall in income and emissions.

The second parameter we consider is b^{ψ}, which governs the correlation between tangible capital and leverage. We estimate this parameter to be $b^{\psi} = 0.43$, as discussed in Section 4.3. Nonetheless, we simulate the economy with a smaller value ($b^{\psi} = 0.30$) and a larger one ($b^{\psi} = 0.50$) to verify the robustness of our conclusions. Not surprisingly, emissions and GDP fall by less for smaller values of b^{ψ}. The reason is that the correlation between tangible capital and leverage is crucial to generate the correlation between changes in output and carbon intensity discussed in Section 4.4.

5 Conclusion

This paper studies the environmental impact of corporate profit taxation. We document that profit taxes are distorted in favor of dirty firms, and that the distortion stems from the fiscal advantage of corporate debt: dirty firms use more tangible capital, therefore, they can borrow more and enjoy a higher tax shield. Finally, we build a general-equilibrium framework with carbon emissions and study the aggregate implications of different corporate taxation reforms. The model suggests that a simple policy that removes the tax shield of debt can substantially reduce carbon emissions in steady state. By effectively making debt more expensive, the same policy, we conjecture, will bring the additional benefit of reducing firm leverage in those sectors that rely more heavily on tangible capital, i.e., the dirty ones. It can thus alleviate the significant financial stability concerns arising from polluting firms' exposure to transition risk and stranded assets; an intriguing avenue to explore that we leave for future research.

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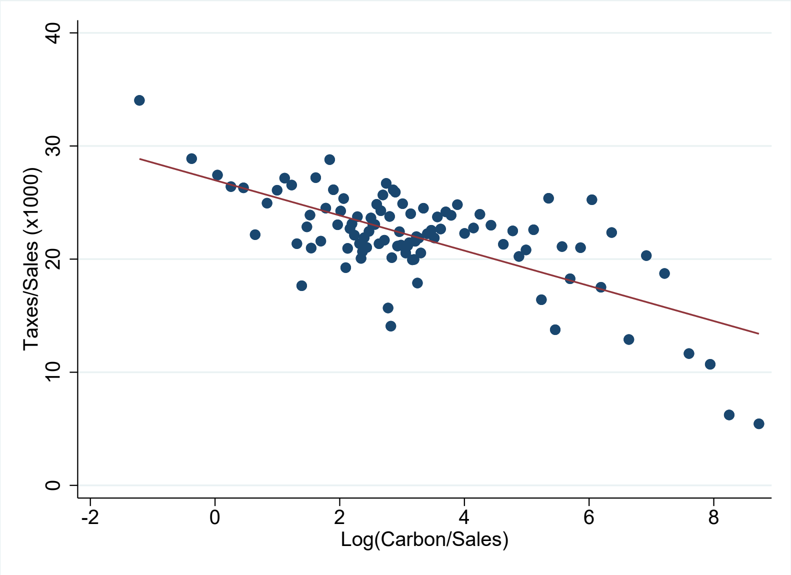
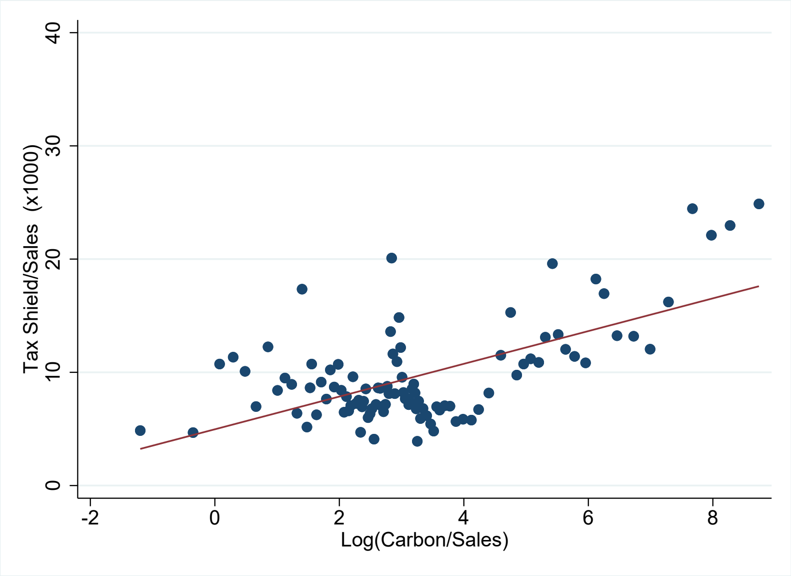
Figure 1. The tax advantage of carbon-intensive firms

Panel A. Taxes



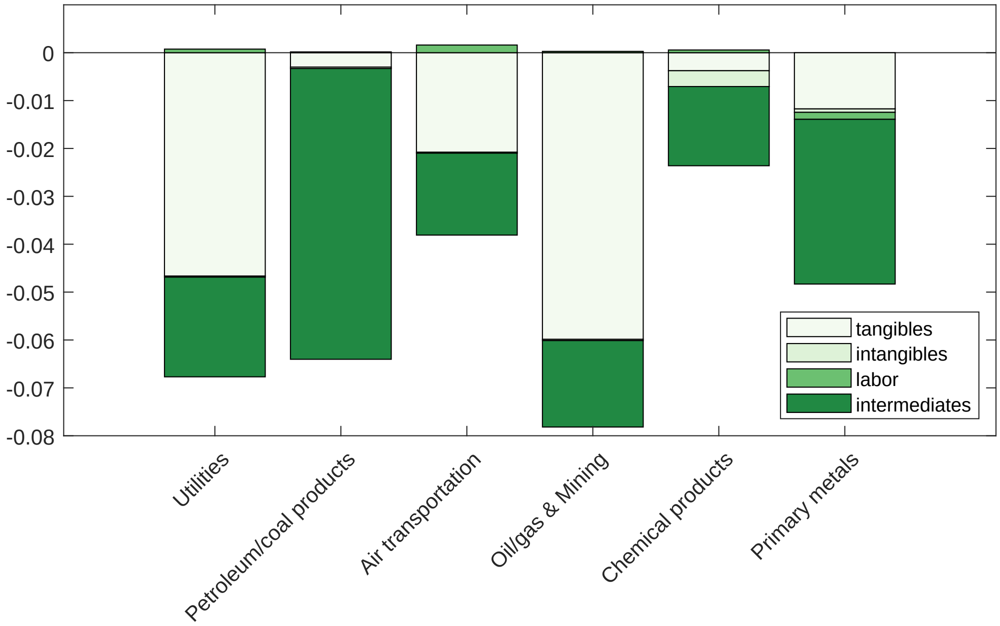
Panel B. Tax Shield



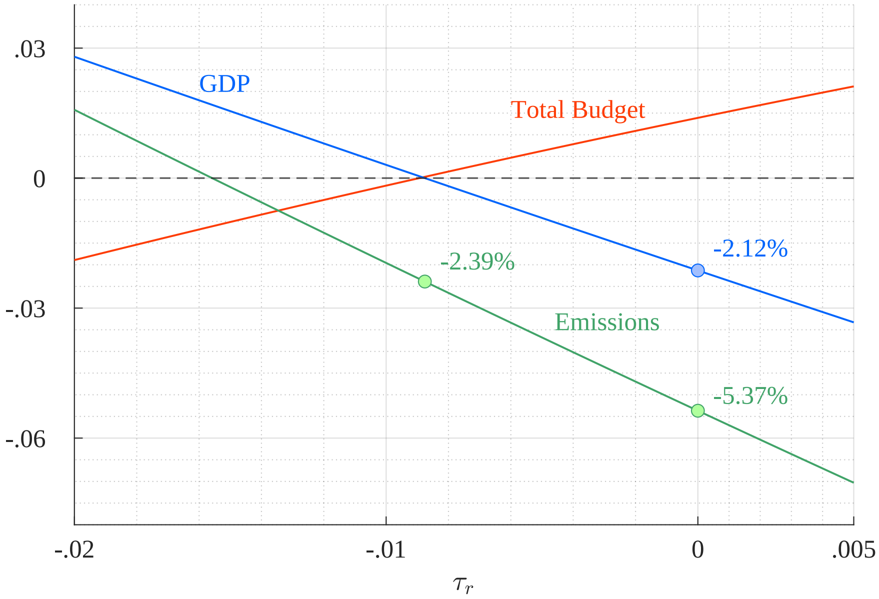
Note: This scatter plot reports the relationship between the logarithm of firms' carbon emissions over total sales and respectively taxes over sales (Panel A), and tax shield over sales (Panel B) over the sample period 2004-2019, after absorbing year fixed effects. Each dot represents an equal size bin of firms' carbon emissions over total sales (100 bins). Taxes are Compustat item TXPD, scaled by sales. Tax shield is computed as interest payments times the firm-level statutory tax rate scaled by firm sales. Data on carbon emissions are from Trucost. Financial data are from Compustat.

Figure 2. Counterfactuals

Panel A. Counterfactual economy without the tax shield



Panel B. Budget-neutral policy



Note: Panel A: Response of output and different inputs to a policy that removes the tax shield of debt, for the six most carbon-intensive sectors. Panel B: The graph plots the change in total government budget (red), aggregate GDP (blue) and total carbon emissions (green) following a policy reform that removes the tax shield of debt and, at the same time, introduces the revenue tax indicated on the horizontal axis (negative values denote subsidies).

Table 2. Summary statistics

	Obs.	Mean	SD	p1	p50	p99
Carbon Emissions						
Carbon/Sales (tonnes of CO_2 per k. Sales)	13,791	0.220	0.712	0.000	0.019	4.627
Taxes paid by U.S. corporations						
Taxes/Sales	13,791	0.022	0.026	-0.020	0.015	0.126
Tax Shield/Sales	13,791	0.010	0.015	0.000	0.005	0.082
Firm Tax Rate (in %)	13,791	33.737	5.225	22.956	35.000	40.841
Other variables						
Sales (in USD Million)	13,791	11,020	31,684	23	2,826	145,224
Firm Age	13,791	45.766	30.215	4.000	39.000	128.000
EBITDA/Sales	13,791	0.117	0.400	-2.736	0.155	0.622
Share Foreign	13,791	0.267	0.274	0.000	0.189	0.944
Debt/Sales	13,791	0.511	0.643	0.000	0.300	3.526
Interest Rate (in %)	13,791	6.791	5.055	1.286	5.623	29.564
PPE/Sales	13,791	0.563	0.916	0.010	0.204	4.704

Note: This table presents summary statistics for our sample, which consists of 13,791 firm-year observations between 2004 and 2019. There are 1,923 Compustat firms in this sample for which we observe carbon emissions in at least one year over the sample period. Data on carbon emissions are from Trucost. Financial data are from Compustat North America Fundamentals. Carbon/Sales is expressed in tonnes of CO_2 equivalent per thousands of sales. Taxes are Compustat item TXPD. Interest payments are Compustat item XINT. Tax shield is computed as interest payments times the firm-level statutory tax rate, defined as in formula (1). Debt is the sum of short term debt (Compustat item DLC) and long term debt (Compustat item DLTT). Share Foreign is the share of sales outside the U.S. retrieved from Factset. Property, plant, and equipment (PPE) is Compustat item PPENT. Interest rate is defined as the ratio of interest payments over beginning-of-period debt.

Table 3. Corporate taxes and carbon emissions

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A:	Taxes per k. Sales					
Carbon Intensity	-4.133***	-4.450***	-4.357***	-4.148***	-6.373***	-6.369***
(tonnes of CO_2 per k. Sales)	(0.578)	(0.571)	(0.670)	(1.102)	(1.158)	(1.109)
Year FE	Y	Y		Y	Y	
HQ State x Year FE			Y			Y
Firm Controls		Y	Y		Y	Y
Size Weights				Y	Y	Y
R^2	0.071	0.135	0.190	0.041	0.336	0.416
N	13,791	13,791	13,791	13,791	13,791	13,791

Panel B:	Tax Shield per k. Sales			Hypothetical Taxes Assuming 100% Equity (per k. Sales)		
Carbon Intensity	4.355***	4.496***	4.445***	0.089	0.090	0.128
(tonnes of CO_2 per k. Sales)	(0.565)	(0.638)	(0.525)	(1.007)	(1.036)	(1.030)
Year FE	Y	Y		Y	Y	
HQ State x Year FE			Y			Y
Firm Controls		Y	Y		Y	Y
R^2	0.050	0.147	0.206	0.046	0.052	0.104
N	13,791	13,791	13,791	13,791	13,791	13,791

Note: This table presents estimates from pooled OLS specifications of taxes over sales on the ratio of firms' carbon emissions over sales. In Panel A the outcome variable is income taxes paid scaled by sales. Specifications are weighted with firms' lagged sales in columns (4) to (6). In Panel B the outcome variable is tax shield in columns (1) to (3) and hypothetical taxes assuming firms are 100% equity financed in columns (4) to (6), both scaled by firms' sales. Tax shield is computed as interest payments times the firm-level statutory tax rate. Hypothetical taxes assuming firms are 100% equity-financed are computed as the sum of income taxes paid and tax shield. Columns (1), (2), (4), and (5) include year fixed effects, whereas columns (3) and (6) include (firms' headquarters) state-year fixed effects. Columns (2), (3), (5), and (6) further include profit (scaled by firms' sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms' headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

Table 4. Corporate taxes, tax shield and carbon emissions - Robustness

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A:	Taxes per k. Sales								
Carbon Intensity	-3.435***	-3.735***	-4.183***	-6.669***	-4.093***	-4.516***	-4.188***	-3.932***	
(tonnes of CO_2 per k. Sales)	(0.879)	(0.716)	(1.521)	(1.306)	(0.875)	(0.603)	(0.676)	(0.639)	
R^2	0.270	0.272	0.219	0.359	0.202	0.172	0.189	0.190	
N	2,686	4,079	9,547	2,321	11,141	11,576	13,791	13,791	
Panel B:	Tax Shield per k. Sales								
Carbon Intensity	4.659***	4.214***	4.975***	3.631***	4.808***	4.500***	4.331***	3.617***	3.753***
(tonnes of CO_2 per k. Sales)	(0.725)	(0.594)	(0.962)	(0.500)	(0.741)	(0.778)	(0.517)	(0.520)	(0.471)
R^2	0.334	0.263	0.156	0.511	0.200	0.216	0.206	0.199	0.199
N	2,686	4,079	9,547	2,321	11,141	11,576	13,791	13,791	12,494
HQ State x Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y
Robustness Test	Private	Domestic	International	Reported	Estimated	EPA	Scope 1+2	Scope 1+2+3	Marginal

Note: This table presents estimates from pooled OLS specifications of taxes over sales (Panel A) and tax shield over sales (Panel B) on firms' carbon emissions over sales. Column (1) presents estimates from a sample of private firms from Refinitiv. Column (2) restricts the sample to domestic firms, column (3) to multinational firms, column (4) to firms with reported carbon emission data, and column (5) to firms with estimated carbon emission data. Column (6) uses EPA data on firms' carbon emissions from stationary sources, available from 2010 onwards. Column (7) considers the sum of scope 1 and 2 emissions to measure carbon intensity, while column (8) uses the sum of scope 1, scope 2, and scope 3 emissions. Column (9) uses firms' marginal tax rates developed in Blouin, Core, and Guay (2010) to compute the tax shield. All columns include (firms' headquarters) state-year fixed effects and profit (scaled by firms' sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms' headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

Table 5. Carbon-intensity, debt and asset tangibility

Panel A:	(1) Debt/Sales	(2) Interest Rate (in %)	(3) Tax Rate (in %)
Carbon Intensity	0.218***	-0.018	-0.007
(tonnes of CO_2 per k. Sales)	(0.022)	(0.091)	(0.037)
HQ State x Year FE	Y	Y	Y
Firm Controls	Y	Y	Y
R^2	0.158	0.138	0.856
N	13,791	13,791	13,791

Panel B:	PPE/Sales	Debt/Sales	Tax Shield per k. Sales
Carbon Intensity	0.511***	-0.014	0.076
(tonnes of CO_2 per k. Sales)	(0.035)	(0.027)	(0.585)
PPE/Sales		0.454***	8.658***
		(0.040)	(0.688)
HQ State x Year FE	Y	Y	Y
Firm Controls	Y	Y	Y
R^2	0.323	0.439	0.401
N	13,791	13,791	13,791

Note: This table presents estimates from pooled OLS specifications of the tax shield components on firms' carbon emissions over sales in Panel A. Panel B explores the role of plant, property and equipment over sales. In Panel A the outcome variable is debt over sales in column (1), interest rate on debt in column (2), and firm-level tax rate in column (3). Debt is the sum of short term and long-term debt. Interest rate is defined as the ratio of interest payments over beginning-of-period debt. In Panel B the outcome variable is plant, property and equipment over sales in column (1), debt over sales in columns (2), and tax shield in columns (3). Tax shield is computed as interest payments times the firm-level statutory tax rate, and is then scaled by firm sales. All columns include (firms' headquarters) state-year fixed effects, as well as profit (scaled by firms' sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms' headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

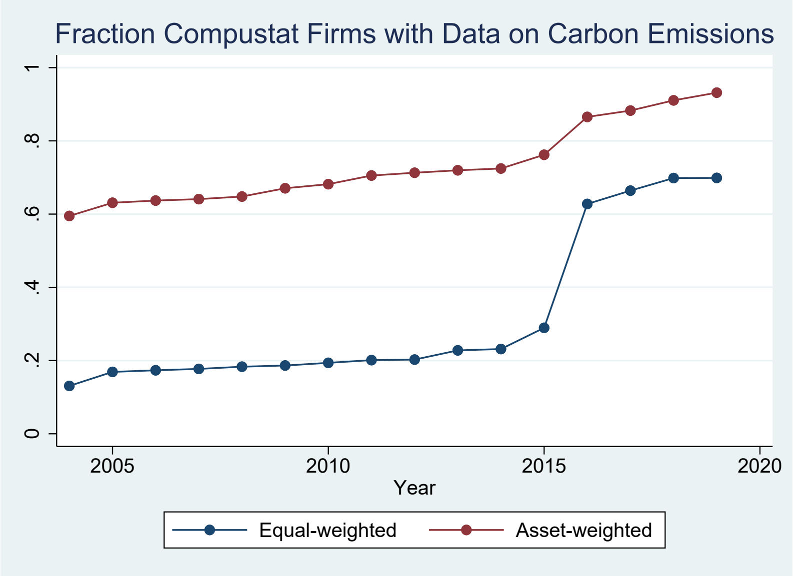
Online Appendix

Corporate Taxation and Carbon Emissions

Luigi Iovino and Thorsten Martin and Julien Sauvagnat

A Additional Figures and Tables

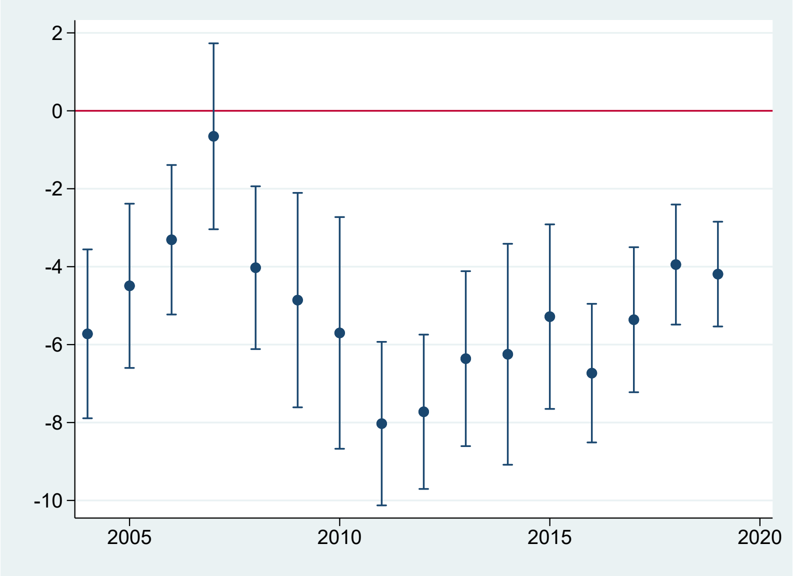
Figure A.1. Coverage of Compustat firms with data on carbon emissions in Trucost



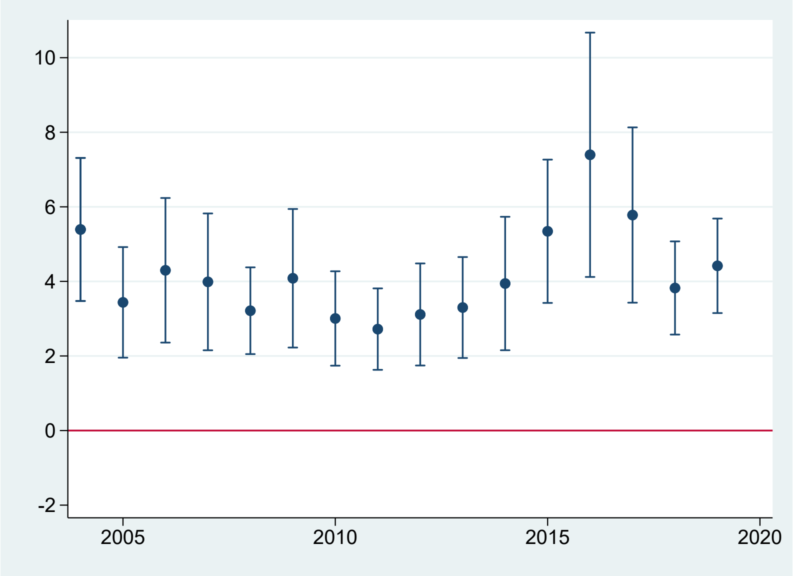
Note: This figure reports the fraction of Compustat firms for which we observe information on carbon emissions in Trucost.

Figure A.2. The tax advantage of carbon-intensive firms - yearly estimates

Panel A. Taxes



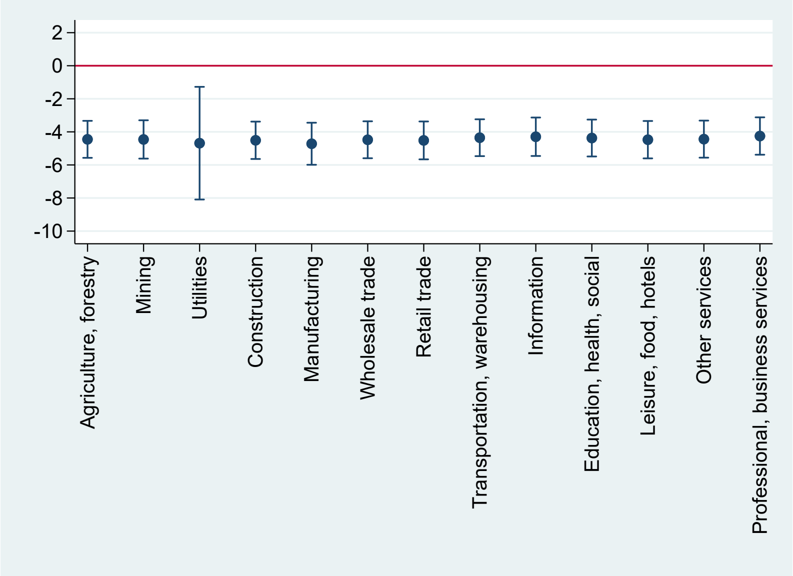
Panel B. Tax Shield



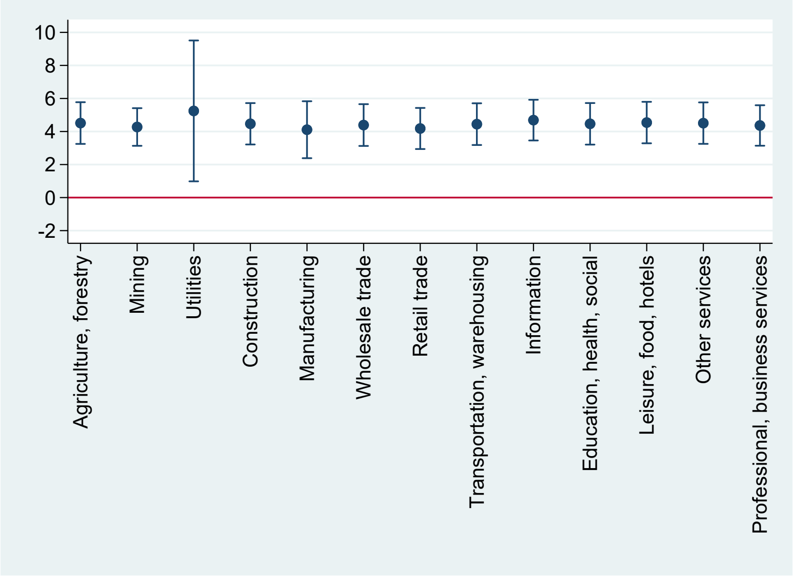
Note: This figure displays yearly estimates of cross-sectional regressions of respectively taxes over sales (Panel A), and tax shield over sales (Panel B) on the ratio of firms' carbon emissions over sales for the sample period 2004-2019, after absorbing (headquarter) state fixed effects and controlling for profit over sales, firm size, firm age, and the share of foreign sales. Standard errors are clustered at the 4-digit industry level. Data on carbon emissions are from Trucost. Financial data are from Compustat North America Fundamentals.

Figure A.3. The tax advantage of carbon-intensive firms - leave-one-out sector

Panel A. Taxes



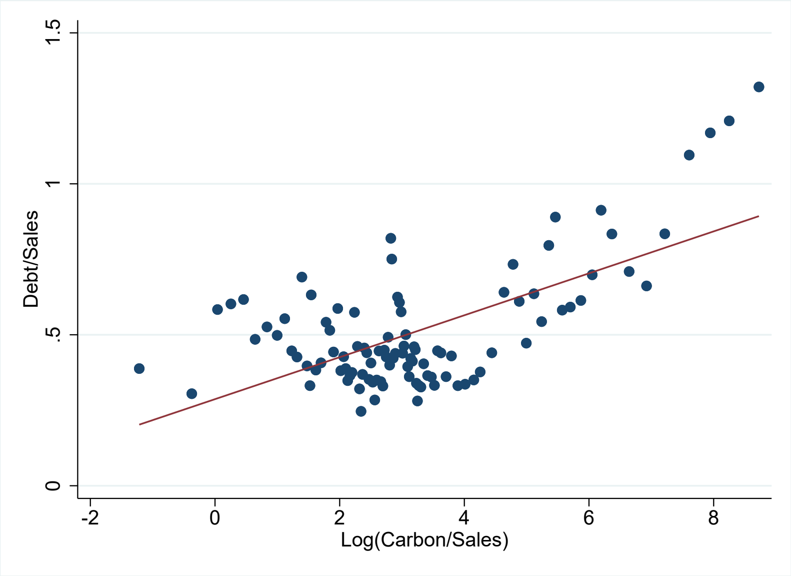
Panel B. Tax Shield



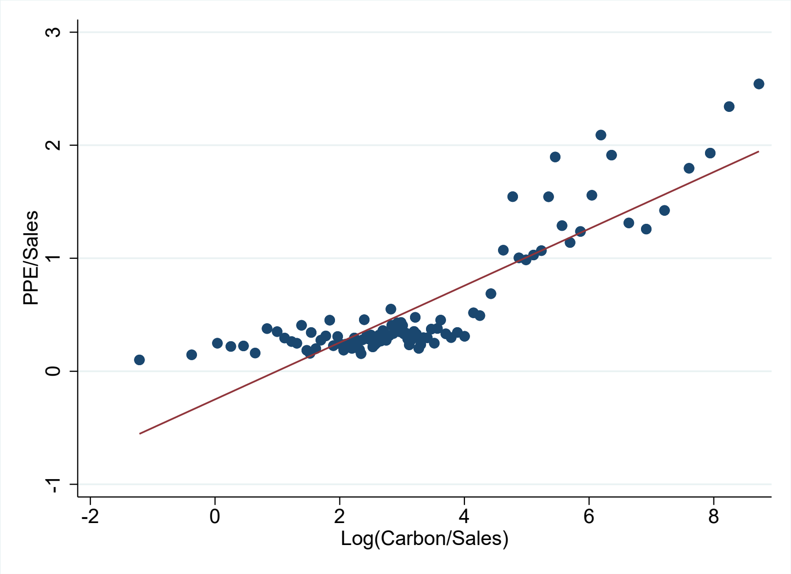
Note: This figure displays estimates of pooled OLS regressions of respectively taxes over sales (Panel A), and tax shield over sales (Panel B) on the ratio of firms' carbon emissions over sales for the sample period 2004-2019 in leave-one-out specifications in which we exclude observations for firms in a given BEA sector, after absorbing (headquarter) state-year fixed effects and controlling for profit over sales, firm size, firm age, and the share of foreign sales. Standard errors are clustered at the 4-digit industry level. Tax shield is computed as interest payments times the firm-level statutory tax rate scaled by firm sales. Data on carbon emissions are from Trucost. Financial data are from Compustat.

Figure A.4. Carbon-intensity, leverage, and asset tangibility

Panel A. Leverage

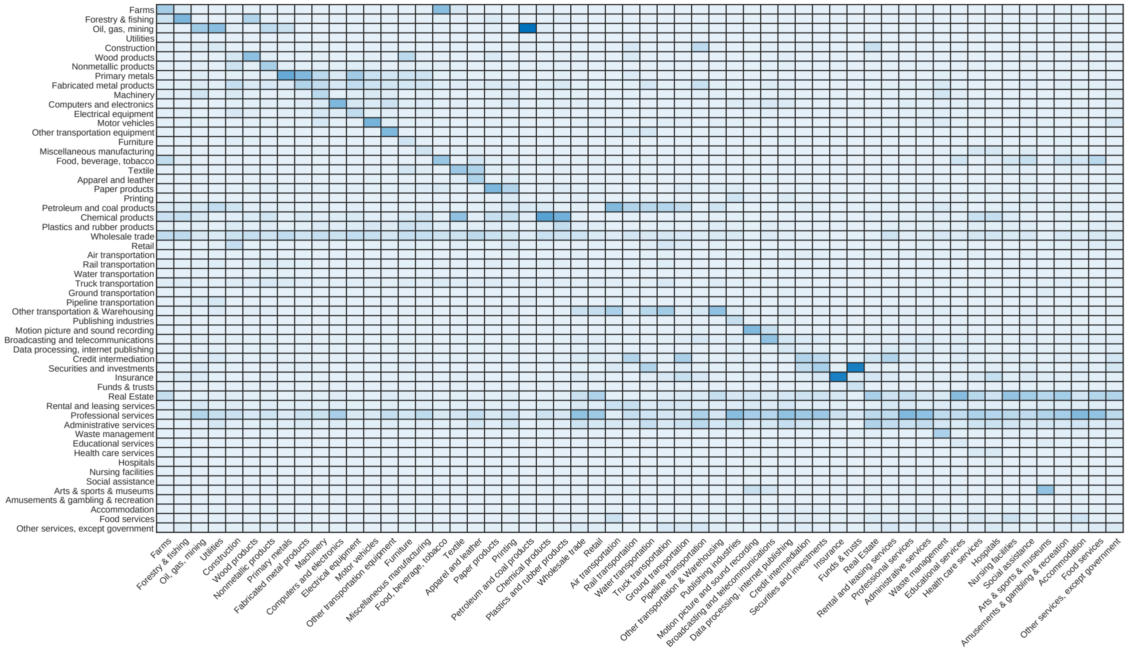


Panel B. Asset Tangibility

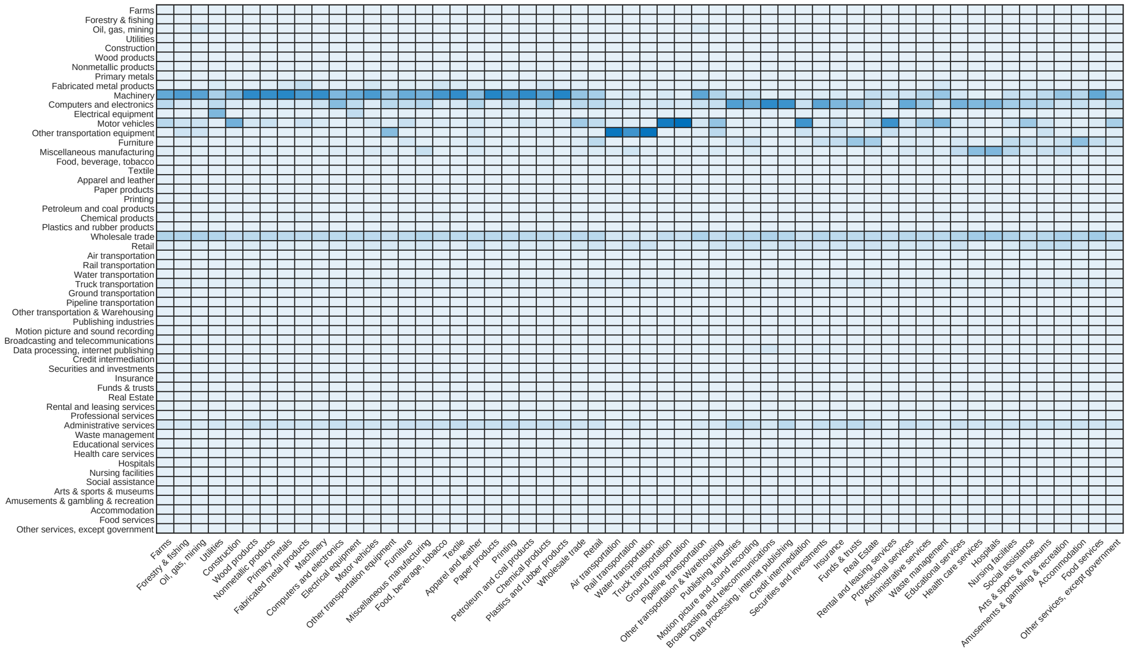


Note: This scatter plot reports the relationship between the logarithm of firms' carbon emissions over total sales and either debt over sales (in Panel A) or property, plant, and equipment over sales (in Panel B) over the sample period 2004-2019, after absorbing year fixed effects. Each dot represents an equal size bin of firms' carbon emissions over total sales (100 bins). Debt over sales is defined as Compustat variables DLC and DLTT over sales. Property, plant, and equipment is Compustat PPENT over sales. Data on carbon emissions are from Trucost. Financial data are from Compustat North America Fundamentals.

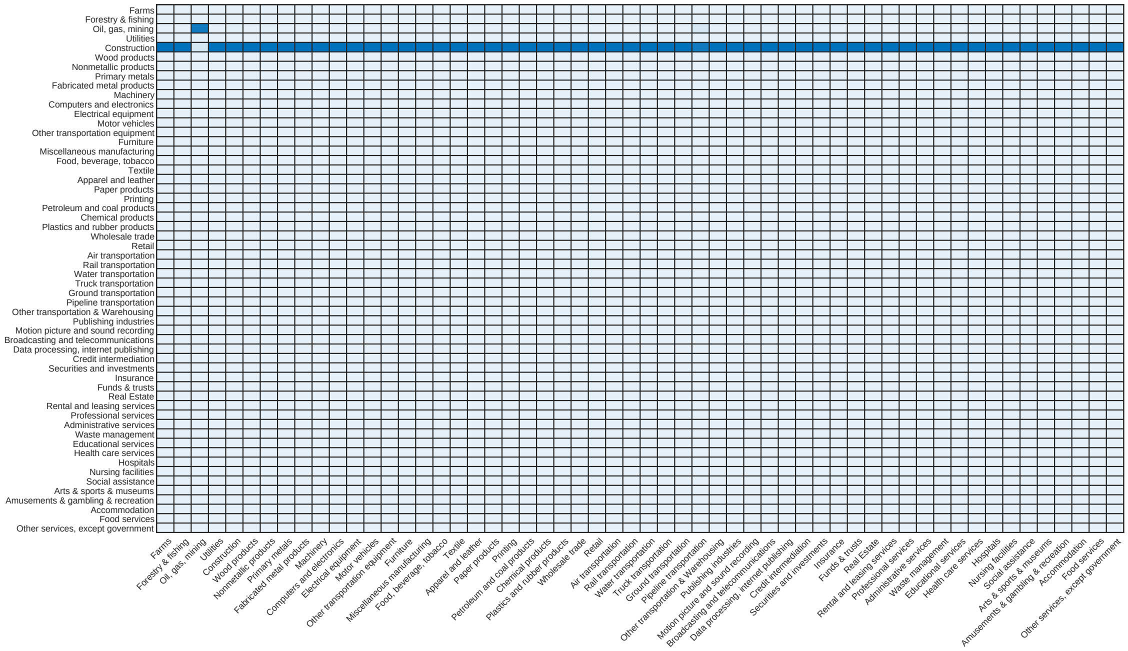
Figure A.5. Networks for intermediates and three types of investment.



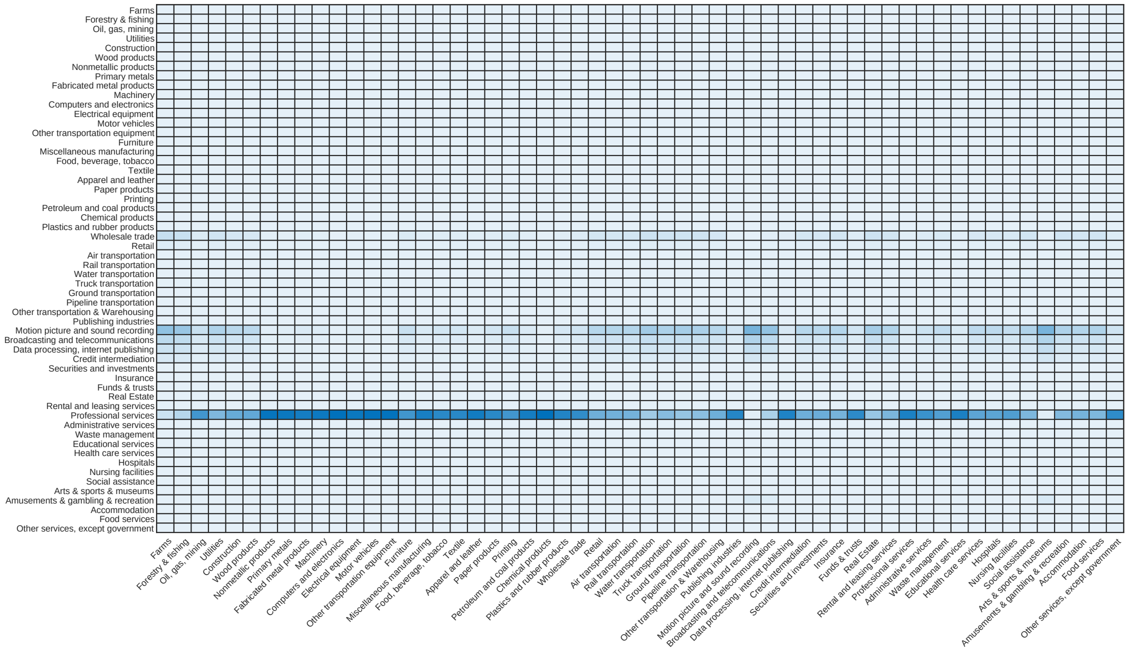
(a) Intermediates



(b) Equipment



(c) Structures



(d) Intangibles

Note: The intermediates network is constructed from the BEA Industry Accounts (Use Tables, sample 2004-2018). The investment networks are constructed following the methodology in vom Lehn and Winberry (2021), which we extend to 56 industries and to 3 different types of investment networks. Data on assets comes from the BEA Fixed Asset tables. In particular, non-residential structures (which we refer to as "structures") are produced mostly from the "Construction" sector; Intellectual Property (which we refer to as "intangibles") comprises 4 types assets: prepackaged software, own and custom software, research and development, and artistic originals; non-residential equipment (which we refer to as "equipment") consists of 25 types of assets.

Table A.1. Taxes, tax shield and carbon emissions - Log carbon/sales

	Taxes per k. Sales			Tax Shield per k. Sales		
Log(Carbon Intensity)	-1.568***	-1.744***	-1.600***	1.441***	1.505***	1.398***
	(0.438)	(0.414)	(0.466)	(0.467)	(0.470)	(0.443)
Year FE	Y	Y		Y	Y	
HQ State x Year FE			Y			Y
Firm Controls		Y	Y		Y	Y
R^2	0.071	0.136	0.188	0.039	0.136	0.192
N	13,791	13,791	13,791	13,791	13,791	13,791

Note: This table presents estimates from pooled OLS specifications of taxes over sales and tax shield over sales on the logarithm of the ratio of firms' carbon emissions over sales. Tax shield is computed as interest payments times the firm-level statutory tax rate, and is then scaled by firm sales. Columns (1), (2), (4), and (5) include year fixed effects, whereas columns (3) and (6) include (firms' headquarters) state-year fixed effects. Columns (2), (3), (5), and (6) further include profit (scaled by firms' sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms' headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

Table A.2. Carbon-intensity, debt and tangibility - Controlling for other determinants of leverage

	(1)	(2)	(3)	(4)	(5)	(6)
		Debt/Sales			Tax Shield per k. Sales	
Carbon Intensity	0.219^{***}	0.173^{***}	-0.021	4.362^{***}	3.611^{***}	0.053
(tonnes of CO_2 per k. Sales)	(0.021)	(0.022)	(0.025)	(0.449)	(0.517)	(0.570)
PPE/Sales			0.432^{***}			8.018^{***}
			(0.036)			(0.689)
Rated		0.384^{***}	0.232^{***}		7.961^{***}	5.179^{***}
		(0.052)	(0.025)		(1.211)	(0.582)
Dividend Payer		0.020	-0.044^{**}		0.061	-1.197^{**}
		(0.034)	(0.022)		(0.788)	(0.575)
M/B		-0.052^{***}	-0.021^{*}		-0.892^{**}	-0.261
		(0.016)	(0.012)		(0.375)	(0.300)
Cash-Flow Volatility		0.105	0.094^{**}		7.721^{**}	7.474^{***}
		(0.095)	(0.046)		(3.013)	(1.871)
Depreciation/Assets		0.076	-2.184^{***}		38.134^{**}	-4.203
		(0.807)	(0.534)		(18.923)	(12.970)
RD/Sales		0.743^{**}	0.420^{*}		12.772^{*}	6.007
		(0.304)	(0.223)		(6.962)	(5.657)
Advertising/Sales		-0.123	0.715^{**}		-12.063	4.417
		(0.396)	(0.359)		(7.337)	(6.161)
EBITDA/Sales		0.296	0.021		-0.570	-6.321^{*}
		(0.234)	(0.148)		(4.909)	(3.304)
Log(Sales)		-0.068^{***}	-0.012		-1.975^{***}	-0.940^{***}
		(0.016)	(0.009)		(0.353)	(0.207)
Log(Firm Age)		-0.065^{**}	-0.061^{***}		-1.092	-0.932
		(0.031)	(0.021)		(0.790)	(0.574)
Share Foreign		-0.209^{***}	-0.010		-6.995^{***}	-3.275^{***}
		(0.066)	(0.047)		(1.419)	(1.104)
HQ State x Year FE	Y	Y	Y	Y	Y	Y
R^2	0.138	0.255	0.482	0.118	0.286	0.434
N	13,791	13,520	13,520	13,791	13,520	13,520

Note: This table presents the same specifications as in columns (2) and (3) of Table 5 in which we further control for a series of other determinants of firm leverage: a dummy variable to indicate if the firm has a credit rating *Rated*, a dummy variable set to one if the firm pays a dividend *Dividend Payer*, the market-to-book ratio M/B, the volatility of firms' cash-flows (scaled by assets) computed over the past five years, depreciation expenses, research and development expenses, and advertising expenses.

Table A.3. Decomposing the relationship between carbon intensity and PPE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Without Firm Controls	GrossPPE/Sales	Machinery/Sales	Buildings/Sales	Leases/Sales	Land/Sales	ConstrInProg/Sales	Other/Sales
Carbon Intensity	0.529***	0.482***	-0.009	-0.022***	0.009	0.015**	0.003
(tonnes of CO_2 per k. Sales)	(0.110)	(0.097)	(0.021)	(0.007)	(0.009)	(0.007)	(0.007)
HQ State x Year FE	Y	Y	Y	Y	Y	Y	Y
R^2	0.228	0.196	0.316	0.172	0.202	0.140	0.085
N	8,132	8,132	8,132	8,132	8,132	8,132	8,132
Panel B: With Firm Controls	GrossPPE/Sales	Machinery/Sales	Buildings/Sales	Leases/Sales	Land/Sales	ConstrInProg/Sales	Other/Sales
Carbon Intensity	0.530***	0.479***	-0.012	-0.018***	0.009	0.015**	0.004
(tonnes of CO_2 per k. Sales)	(0.107)	(0.093)	(0.022)	(0.006)	(0.009)	(0.007)	(0.007)
HQ State x Year FE	Y	Y	Y	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y	Y	Y	Y
R^2	0.237	0.208	0.323	0.297	0.213	0.147	0.092
N	8,132	8,132	8,132	8,132	8,132	8,132	8,132
Dep Var Mean	0.534	0.309	0.105	0.038	0.022	0.016	0.020

Note: This table presents estimates from pooled OLS specifications where the dependent variables correspond to the different components of plant, property and equipment (PPE) (scaled by sales), namely ”machinery and equipment”, ”buildings”, ”leases”, ”land and improvements”, ”construction in progress”, ”natural resources” and ”other”. We sum the items ”natural resources” and ”other”, and label it ”other”, as the item ”natural resources” represent a tiny fraction of PPE. The data is before substracting accumulated depreciation. Information on the different components of PPE is not available for utilities. We exclude observations for which the sum of the components differ from total PPE by more than 10%. All columns in both panels include (firms’ headquarters) state-year fixed effects. Panel B further includes profit (scaled by firms’ sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms’ headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. The last row reports the sample average of the dependent variable in each column. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

Table A.4. Tangibility, debt, tax shield, taxes and carbon emissions - Industry effects

	(1) PPE/Sales	(2) Debt/Sales	(3) Tax Shield per k. Sales	(4) Taxes per k. Sales
Implied Industry Carbon Intensity	0.819^{***}	0.327^{***}	6.861^{***}	-6.978^{***}
	(0.081)	(0.050)	(1.066)	(1.010)
Firm Residual Carbon Intensity	0.241^{***}	0.119^{***}	2.075^{***}	-2.041^{**}
	(0.078)	(0.028)	(0.640)	(0.853)
HQ State x Year FE	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y
R^2	0.359	0.164	0.213	0.193
N	13,791	13,791	13,791	13,791

Note: This table presents estimates from pooled OLS specifications of firms' tangibility, leverage, tax shield, and taxes on the industry carbon intensity implied by firms' sales across different industries and firms' residual carbon intensity. Implied industry carbon intensity is computed as the weighted-average industry carbon intensity across firms' business units. Industry carbon intensity is computed as the average carbon scaled by sales ratio across firms operating only in one industry. Firm residual carbon intensity are the residuals of regressing firm-level carbon intensity on implied industry carbon intensity. Tax shield is computed as interest payments times the firm-level statutory tax rate, and is then scaled by firm sales. All columns include (firms' headquarters) state-year fixed effects and profit (scaled by firms' sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms' headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

Table A.5. Tangibility, debt, tax shield, taxes and carbon emissions - Energy sector

	(1) Carbon Intensity	(2) PPE/Sales	(3) Debt/Sales	(4) Tax Shield per k. Sales	(5) Taxes per k. Sales
Panel A:	Carbon intensity				
Carbon Intensity		0.278***	0.118***	2.648***	-2.898**
(tonnes of CO_2 per k. Sales)		(0.076)	(0.041)	(0.942)	(1.408)
Year FE		Y	Y	Y	Y
Firm Controls		Y	Y	Y	Y
R^2		0.559	0.294	0.335	0.236
N		969	969	969	969
Panel B:	Fossil fuel energy production capacity				
Fossil Fuel Capacity	0.609***	0.190***	0.090***	2.262***	-2.748**
(gigawatts per k. Sales)	(0.058)	(0.065)	(0.027)	(0.646)	(1.056)
Year FE	Y	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y	Y
R^2	0.637	0.448	0.217	0.263	0.246
N	969	1,296	1,296	1,296	1,296

Note: This table presents estimates from pooled OLS specifications of firms' tangibility, leverage, tax shield, and taxes on carbon intensity within the energy sector. Carbon intensity is measured using data on carbon emissions from stationary sources reported under the EPA Greenhouse Gas Reporting program scaled by sales. Fossil fuel capacity is measured in gigawatts using EIA data on energy generators reported under the form 860. We aggregate the nameplate capacity of operating generators with main energy source coal, petroleum or natural gas to the firm owning the generator. We restrict the sample to firms operating energy generators reporting to the EIA. Tax shield is computed as interest payments times the firm-level statutory tax rate, and is then scaled by firm sales. All columns include (firms' headquarters) state-year fixed effects and profit (scaled by firms' sales), firm size, firm age, and the share of foreign sales as control variables. Information about firms' headquarters are retrieved from Infogroup. Standard errors clustered at the 4-digit SIC industry level are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

Table A.6. List of sectors used for policy counterfactuals

Farms
Forestry, fishing, and related activities
Oil and gas extraction + Mining + Support activities for mining
Utilities
Construction
Wood products
Nonmetallic mineral products
Primary metals
Fabricated metal products
Machinery
Computer and electronic product
Electrical equipment, appliances, and components
Motor vehicles, bodies and trailers, and parts
Other transportation equipment
Furniture and related products
Miscellaneous manufacturing
Food and beverage and tobacco products
Textile mills and textile product mills
Apparel and leather and allied products
Paper products
Printing and related support activities
Petroleum and coal products
Chemical products
Plastics and rubber products
Wholesale trade
Retail
Air transportation
Rail transportation
Water transportation
Truck transportation
Transit and ground passenger transportation
Pipeline transportation
Other transportation + Warehousing and storage
Publishing industries, except internet (includes software)
Motion picture and sound recording industries
Broadcasting and telecommunications
Data processing, internet publishing, and other information services
Federal Reserve banks, credit intermediation, and related activities
Securities, commodity contracts, and investments
Insurance carriers and related activities
Funds, trusts, and other financial vehicles
Real Estate
Rental and leasing services and lessors of intangible assets
Legal services + Computer systems design + Miscellaneous professional, scientific, and technical services Management of companies and enterprises
Administrative and support services
Waste management and remediation services
Educational services
Ambulatory health care services
Hospitals Nursing and residential care facilities
Social assistance
Performing arts, spectator sports, museums, and related activities
Amusements, gambling, and recreation industries
Accommodation
Food services and drinking places
Other services, except government

B Proofs

Household. We begin with the household's problem. We first minimize total expenditures

$$\sum_{i\in\mathcal{N}}\int p^f_{i,t}c^f_{i,t}df,$$

subject to achieving some level of aggregate consumption $C_t \equiv \prod_i (c_{i,t}/\theta_i)^{\theta_i}$, where consumption on goods from sector i is $c_{i,t} \equiv \left(\int (c^f_{i,t})^{\frac{\sigma_i-1}{\sigma_i}}df\right)^{\frac{\sigma_i}{\sigma_i-1}}$. We obtain the standard demand schedule

$$c^f_{i,t} = \left(\frac{p^f_{i,t}}{p_{i,t}}\right)^{-\sigma_i} c_{i,t}, \tag{B.1}$$

where $p_{i,t} \equiv \left(\int (p^f_{i,t})^{1-\sigma_i}df\right)^{\frac{1}{1-\sigma_i}}$ is the appropriate price index for sector i. In addition, the Cobb-Douglas specification implies

$$p_{i,t}c_{i,t} = \theta_i C_t, \tag{B.2}$$

where we normalize $P_t \equiv \prod_i p^{\theta_i}_{i,t} = 1$. The latter coincides with (8).

Next, we choose C_t. Letting φ_t be the Lagrange multiplier on the household's budget constraint, we obtain

$$U'(C_t) = (1+\tau_c)\varphi_t. \tag{B.3}$$

Similarly, the optimal choice of L_t satisfies the first-order condition

$$V'(L_t) = (1-\tau_h)\varphi_t w_t. \tag{B.4}$$

Combining (B.3) and (B.4), we obtain (9).

Finally, we consider the portfolio problem. Since default and liquidation shocks are i.i.d. across firms, in every period there will be exactly a fraction $\rho_i + \lambda_i$ of firms in default and a fraction λ_i of firms in liquidation. The first-order conditions for the optimal choices of risk-free bonds, corporate bonds and equity are, respectively,

$$\varphi_t = \varphi_{t+1}(1+(1-\tau_h)r_t),$$

$$\varphi_t = \varphi_{t+1} + \varphi_{t+1}(1-\lambda_i)(1-\tau_h)r^b_{i,t+1} - \varphi_{t+1}\lambda_i(1-\tau_h),$$

and

$$\varphi_t Q^f_{i,t} = \varphi_{t+1}(1-\rho_i-\lambda_i)(1-\tau_d)(d^f_{i,t+1}+Q^f_{i,t+1}) + \varphi_{t+1}\tau_d Q^f_{i,t}.$$

Combining the first two conditions, we obtain

$$r^b_{i,t+1} = \frac{\lambda_i + r_t}{1 - \lambda_i},$$

which coincides with (10). Similarly, the first and third conditions together give

$$r^e_{i,t+1} \equiv \frac{d^f_{i,t+1} + Q^f_{i,t+1}}{Q^f_{i,t}} - 1 = \frac{(\rho_i + \lambda_i)(1 - \tau_d) + (1 - \tau_h) r_t}{(1 - \rho_i - \lambda_i)(1 - \tau_d)}, \tag{B.5}$$

which is (11).

Note that the expected net return on equity is equal to the net risk-free rate because there is no aggregate risk:

$$(1 - \rho_i - \lambda_i)(1 - \tau_d) r^e_{i,t+1} + (\rho_i + \lambda_i)(-1)(1 - \tau_d) = (1 - \tau_h) r_t.$$

The same property holds for corporate bonds.

Firms. We now turn to the firm's problem. In the main text, to ease notation we considered the representative firm in each sector. Here, instead, we solve the problem of a generic firm f in sector i. The firm maximizes

$$\mathbb{E} \sum_{t=0}^{\infty} \varphi_t d^f_{i,t},$$

subject to

(i) the process for dividends

$$d^f_{i,t} = (1 - \tau_p) TI^f_{i,t} - \sum_{s \in \mathcal{T}} q^s_{i,t} (k^{f,s}_{i,t+1} - k^{f,s}_{i,t}) + b^f_{i,t+1} - b^f_{i,t}, \tag{B.6}$$

and taxable income

$$TI^f_{i,t} = p^f_{i,t} y^f_{i,t} - \sum_{j \in \mathcal{N}} p_{j,t} x^f_{i,j,t} - w_t \ell^f_{i,t} - \sum_{s \in \mathcal{T}} \delta^s_i q^s_{i,t} k^{f,s}_{i,t} - \sum_{s \in \mathcal{I}} q^s_{i,t} I^{f,s}_{i,t} - \sum_{s \in \mathcal{S}} \tau^s_k q^s_{i,t} k^{f,s}_{i,t} - \omega_r r^b_{i,t} b^f_{i,t}, \tag{B.7}$$

where $q^s_{i,t}$ is the price of the investment bundle in type-s capital for sector i (which we define below), and where $\omega_r = 1$ when interest expenses enjoy a tax shield and $\omega_r = 1/(1 - \tau_p)$ otherwise;

(ii) the production function

$$y^f_{i,t} = z_{i,t} \zeta_i \Big(\prod_{j \in \mathcal{N}} (x^f_{i,j,t})^{\alpha_{ij}} \Big)^{1-\gamma_i} \Big((\ell^f_{i,t})^{\phi^\ell_i} \prod_{s \in \mathcal{S}} (k^{f,s}_{i,t})^{\phi^s_i} \Big)^{\gamma_i}; \tag{B.8}$$

(iii) the law of motion for capital

$$k^{f,s}_{i,t+1} = (1 - \delta^s_i) k^{f,s}_{i,t} + I^{f,s}_{i,t}, \tag{B.9}$$

where investment is given by

$$I_{i,t}^{f,s} = \prod_{j\in\mathcal{N}} \left(\frac{i_{i,j,t}^{f,s}}{\omega_{ij}^{s}}\right)^{\omega_{ij}^{s}}; \tag{B.10}$$

(iv) the borrowing constraint

$$b_{i,t+1}^{f} \le \frac{1}{1+r_{i,t+1}^{b}} \sum_{s\in\mathcal{S}} \psi_{i,s} q_{i,t+1}^{s} k_{i,t+1}^{f,s}; \tag{B.11}$$

(v) and the demand schedule

$$y_{i,t}^{f} = \left(\frac{p_{i,t}^{f}}{p_{i,t}}\right)^{-\sigma_i} y_{i,t}. \tag{B.12}$$

Note that monopolistic competitive firms take demand into account when choosing production, this is why (B.12)—which follows from (B.1) and goods-market clearing—enters the maximization problem.

We begin with the choice of labor. Substituting (B.8) and (B.12) into (B.6) and taking the first-order condition with respect to $\ell_{i,t}^{f}$, we obtain

$$\mu_i \gamma_i \phi_i^{\ell} = \frac{w_t \ell_{i,t}^{f}}{p_{i,t}^{f} y_{i,t}^{f}}. \tag{B.13}$$

Similarly, the first-order condition for the optimal choice of $x_{i,j,t}^{f}$ is

$$\mu_i (1-\gamma_i)\alpha_{ij} = \frac{p_{j,t} x_{i,j,t}^{f}}{p_{i,t}^{f} y_{i,t}^{f}}. \tag{B.14}$$

In a symmetric equilibrium all firms in a sector make the same choices, thus, we can drop the superscript f from the notation, and the latter two conditions become (13). Finally, conditional on total investment $I_{i,t}^{f,s}$, the optimal choice of $i_{i,j,t}^{f,s}$ is static and satisfies the first-order condition

$$p_{j,t} i_{i,j,t}^{f,s} - \lambda_{i,t}^{f,s} \omega_{ij} I_{i,t}^{f,s} = 0,$$

where $\lambda_{i,t}^{f,s}$ is the Lagrange multiplier on (B.10). As a result,

$$\sum_{j\in\mathcal{N}} p_{j,t} i_{i,j,t}^{f,s} = q_{i,t}^{s} I_{i,t}^{f,s},$$

where $q_{i,t}^{s} \equiv \prod_j p_{j,t}^{\omega_{ij}^{s}}$ is the price index of sector i's investment bundle. Therefore,

$$i_{i,j,t}^{f,s} = \frac{1}{p_{j,t}} \omega_{ij}^{s} q_{i,t}^{s} I_{i,t}^{f,s}. \tag{B.15}$$

In a symmetric equilibrium, (B.15) becomes (14).

Consider now the choice of debt and investment. We focus on tangible capital, the expressions for intangible capital are analogous. The assumption that $r^e_{i,t+1} \geq r^b_{i,t+1}$, for all i, together with the fact that debt enjoys a tax advantage, imply that firms always prefer borrowing through debt rather than equity. It follows that the borrowing constraint (B.11) will hold with equality, pinning down the optimal choice of debt. Finally, using (B.9) to replace $I^{f,s}_{i,t}$ into (B.6), the optimal choice of $k^{f,s}_{i,t+1}$ satisfies the first-order condition

$$\begin{aligned} -q^s_{i,t} + \frac{1}{1+r^b_{i,t+1}}\psi_{i,s} q^s_{i,t+1} + \frac{1}{1+r^e_{i,t+1}}(1-\tau_p)\Big\{\mu_i\gamma_i\phi^s_i p^f_{i,t+1} y^f_{i,t+1}\frac{1}{k^{f,s}_{i,t+1}} - \delta^s_i q^s_{i,t+1} - \tau^s_k q^s_{i,t+1}\Big\} \\ + \frac{1}{1+r^e_{i,t+1}}\Big\{ -(1-\tau_p)\omega_r \frac{r^b_{i,t+1}}{1+r^b_{i,t+1}}\psi_{i,s} q^s_{i,t+1} + q^s_{i,t+1} - \frac{1}{1+r^b_{i,t+1}}\psi_{i,s} q^s_{i,t+1}\Big\} = 0, \end{aligned}$$

where we have used (B.5). In a symmetric equilibrium, it can be rewritten as

$$\mu_i\gamma_i\phi^s_i = R^s_{i,t}\frac{q^s_{i,t}k^s_{i,t}}{p_{i,t}y_{i,t}}, \tag{B.16}$$

where

$$R^s_{i,t} \equiv \delta^s_i + \tau^s_k + \omega_r r^b_{i,t}\frac{\psi_{i,s}}{1+r^b_{i,t}} + \frac{1}{1-\tau_p}r^e_t\Big(1 - \frac{\psi_{i,s}}{1+r^b_{i,t}}\Big) + \frac{1}{1-\tau_p}(1+r^e_{i,t})\Big(\frac{q^s_{i,t-1}}{q^s_{i,t}} - 1\Big) \tag{B.17}$$

is the appropriate rental rate of type-s capital. When $\omega_r = 1$ (i.e., interest expenses enjoy a tax shield) the latter becomes (15).

Steady state. We now solve for the steady state of the economy. Steady-state variables do not bear a time subscript. Combining equations (B.2) and (B.14) gives

$$\frac{\theta_j/c_j}{\theta_i/c_i} = \frac{p_j}{p_i} = \mu_i\frac{y_i}{x_{i,j}}(1-\gamma_i)\alpha_{ij}$$

or

$$x_{j,i} = \mu_j y_j(1-\gamma_j)\alpha_{ji}\frac{\theta_j c_i}{c_j\theta_i}. \tag{B.18}$$

Summing across goods,

$$\sum_{j\in\mathcal{N}} x_{j,i} = \frac{c_i}{\theta_i}\sum_{j\in\mathcal{N}}\mu_j y_j(1-\gamma_j)\alpha_{ji}\frac{\theta_j}{c_j}.$$

Also, in steady state (B.16) simplifies into

$$\mu_i\gamma_i\phi^s_i = R^s_i\frac{q^s_i k^s_i}{p_i y_i},$$

where the steady-state rental rate is

$$R_i^s \equiv \delta_i^s + \tau_k^s + r_i^e - \frac{1}{1-\tau_p}\Big(r_i^e - (1-\tau_p)\omega_r r_i^b\Big)\frac{\psi_{i,s}}{1+r_i^b}.$$

Combining it with (B.15) yields

$$\frac{p_j i_{i,j}^s}{p_i y_i} = \mu_i \gamma_i \phi_i^s \omega_{ij}^s \frac{\delta_i^s}{R_i^s}. \tag{B.19}$$

Using equation (B.2) with (B.19) we obtain

$$\frac{\theta_j/c_j}{\theta_i/c_i} = \frac{p_j}{p_i} = \mu_i \gamma_i \phi_i^s \omega_{ij}^s \frac{\delta_i^s}{R_i^s} \cdot \frac{y_i}{i_{i,j}^s}$$

or

$$i_{j,i}^s = \mu_j \gamma_j \phi_j^s \omega_{ji}^s \frac{\delta_j^s}{R_j^s} y_j \frac{\theta_j c_i}{c_j \theta_i}. \tag{B.20}$$

Summing across goods and types of capital, we obtain

$$\sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}} i_{j,i}^s = \frac{c_i}{\theta_i}\sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}} \mu_j y_j \gamma_j \phi_j^s \omega_{ji}^s \frac{\delta_j^s}{R_j^s}\cdot\frac{\theta_j}{c_j}.$$

Using the resource constraint (7) yields

$$y_i = c_i + \frac{c_i}{\theta_i}\sum_{j\in\mathcal{N}} \mu_j y_j (1-\gamma_j)\alpha_{ji}\frac{\theta_j}{c_j} + \frac{c_i}{\theta_i}\sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}} \mu_j y_j \gamma_j \phi_j^s \omega_{ji}^s \frac{\delta_j^s}{R_j^s}\cdot\frac{\theta_j}{c_j}. \tag{B.21}$$

It is convenient to work with matrix notation. Given a vector $\boldsymbol{x}$, we let $\operatorname{diag}(\boldsymbol{x})$ denote the diagonal matrix whose main diagonal is given by $\boldsymbol{x}$. Equation (B.21) can then be rewritten as

$$\boldsymbol{y} = \boldsymbol{c} + \operatorname{diag}(\boldsymbol{c})\operatorname{diag}(\boldsymbol{\theta})^{-1}\Delta\operatorname{diag}(\boldsymbol{\theta})\operatorname{diag}(\boldsymbol{c})^{-1}\boldsymbol{y},$$

where $\Delta \equiv A'\operatorname{diag}(\boldsymbol{\mu})\operatorname{diag}(\mathbf{1}-\boldsymbol{\gamma}) + \sum_s (\Omega^s)'\operatorname{diag}(\boldsymbol{\mu})\operatorname{diag}((\boldsymbol{R}^s)^{-1})\operatorname{diag}(\boldsymbol{\delta}^s)\operatorname{diag}(\boldsymbol{\phi}^s)\operatorname{diag}(\boldsymbol{\gamma})$. Thus, letting $I_{\mathcal{N}}$ denote the identity matrix of dimension $N\times N$,

$$\boldsymbol{y} = (I_{\mathcal{N}} - \operatorname{diag}(\boldsymbol{c})\operatorname{diag}(\boldsymbol{\theta})^{-1}\Delta\operatorname{diag}(\boldsymbol{\theta})\operatorname{diag}(\boldsymbol{c})^{-1})^{-1}\boldsymbol{c}$$

or, since $(A^{-1}BA)^{-1} = A^{-1}B^{-1}A$,

$$\boldsymbol{y} = \operatorname{diag}(\boldsymbol{c})\operatorname{diag}(\boldsymbol{\theta})^{-1}(I_{\mathcal{N}} - \Delta)^{-1}\operatorname{diag}(\boldsymbol{\theta})\operatorname{diag}(\boldsymbol{c})^{-1}\boldsymbol{c}.$$

Finally, using $\operatorname{diag}(\boldsymbol{c})^{-1}\boldsymbol{c} = \mathbf{1}$, we obtain

$$\operatorname{diag}(\boldsymbol{\theta})\operatorname{diag}(\boldsymbol{c})^{-1}\boldsymbol{y} = (I_{\mathcal{N}} - \Delta)^{-1}\boldsymbol{\theta}. \tag{B.22}$$

Consider now the equilibrium in the labor market. Combining condition (B.4) and (13) yields

$$\ell_i = \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} \theta_i \phi_i^\ell \gamma_i \mu_i \frac{y_i}{c_i} \tag{B.23}$$

or, in matrix notation,

$$\boldsymbol{\ell} = \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} \operatorname{diag}(\boldsymbol{\phi}^\ell) \operatorname{diag}(\boldsymbol{\mu}) \operatorname{diag}(\boldsymbol{\gamma}) \operatorname{diag}(\boldsymbol{\theta}) \operatorname{diag}(\boldsymbol{c})^{-1} \boldsymbol{y}.$$

Using market clearing for labor (7) and equation (B.22) yields

$$\begin{aligned} L = \mathbf{1}'\boldsymbol{\ell} &= \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} (\boldsymbol{\phi}^\ell)' \operatorname{diag}(\boldsymbol{\mu}) \operatorname{diag}(\boldsymbol{\gamma}) \operatorname{diag}(\boldsymbol{\theta}) \operatorname{diag}(\boldsymbol{c})^{-1} \boldsymbol{y} \\ &= \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} (\boldsymbol{\phi}^\ell)' \operatorname{diag}(\boldsymbol{\mu}) \operatorname{diag}(\boldsymbol{\gamma}) (I_\mathcal{N} - \Delta)^{-1} \boldsymbol{\theta}. \end{aligned} \tag{B.24}$$

If we divide the production function (B.8) by y_i and use the assumption of constant returns to scale, we obtain

$$1 = z_i \zeta_i \prod_{j \in \mathcal{N}} \left(\frac{x_{i,j}}{y_i} \right)^{(1-\gamma_i)\alpha_{ij}} \left(\frac{\ell_i}{y_i} \right)^{\gamma_i \phi_i^\ell} \prod_{s \in \mathcal{S}} \left(\frac{k_i^s}{y_i} \right)^{\gamma_i \phi_i^s}. \tag{B.25}$$

From (B.20),

$$\frac{i_{i,j}^s}{y_i} = \mu_i \gamma_i \phi_i^s \omega_{ij}^s \frac{\delta_i^s}{R_i^s} \cdot \frac{\theta_i c_j}{c_i \theta_j}$$

or, since $I_i^s = \prod_j (i_{i,j}^s / \omega_{ij}^s)^{\omega_{ij}^s}$,

$$\frac{I_i^s}{y_i} = \mu_i \gamma_i \phi_i^s \frac{\delta_i^s}{R_i^s} \cdot \frac{\theta_i}{c_i} \prod_{j \in \mathcal{N}} \left(\frac{c_j}{\theta_j} \right)^{\omega_{ij}^s}.$$

Finally, using the fact that in steady state $I_i^s = \delta_i^s k_i^s$, we obtain

$$\frac{k_i^s}{y_i} = \mu_i \gamma_i \phi_i^s \frac{1}{R_i^s} \cdot \frac{\theta_i}{c_i} \prod_{j \in \mathcal{N}} \left(\frac{c_j}{\theta_j} \right)^{\omega_{ij}^s}. \tag{B.26}$$

From (B.18),

$$\frac{x_{i,j}}{y_i} = \mu_i (1-\gamma_i) \alpha_{ij} \frac{\theta_i c_j}{c_i \theta_j}$$

and, from (B.23),

$$\frac{\ell_i}{y_i} = \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} \theta_i \mu_i \gamma_i \phi_i^\ell \frac{1}{c_i}.$$

Substituting these expressions into (B.25) gives

$$c_i = z_i\zeta_i\theta_i\mu_i \prod_{j\in\mathcal{N}} \left((1-\gamma_i)\alpha_{ij}\frac{c_j}{\theta_j}\right)^{(1-\gamma_i)\alpha_{ij}} \left(\gamma_i\phi_i^\ell \frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right)^{\gamma_i\phi_i^\ell} \prod_{s\in\mathcal{S}} \left(\gamma_i\phi_i^s\frac{1}{R_i^s}\prod_{j\in\mathcal{N}}\left(\frac{c_j}{\theta_j}\right)^{\omega_{ij}^s}\right)^{\gamma_i\phi_i^s},$$

which, using the definition of ζ_i, can be simplified into

$$\frac{c_i}{\theta_i} = z_i\mu_i \prod_{j\in\mathcal{N}} \left(\frac{c_j}{\theta_j}\right)^{(1-\gamma_i)\alpha_{ij}} \left(\frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right)^{\gamma_i\phi_i^\ell} \prod_{s\in\mathcal{S}} \left(\frac{1}{R_i^s}\prod_{j\in\mathcal{N}}\left(\frac{c_j}{\theta_j}\right)^{\omega_{ij}^s}\right)^{\gamma_i\phi_i^s}.$$

Taking logs of both sides,

$$\begin{aligned}\log(c_i/\theta_i) - (1-\gamma_i)\sum_{j\in\mathcal{N}}\alpha_{ij}\log(c_j/\theta_j) - \gamma_i\sum_{s\in\mathcal{S}}\phi_i^s\sum_{j\in\mathcal{N}}\omega_{ij}^s\log(c_j/\theta_j)\\ = \log(z_i\mu_i) + \gamma_i\phi_i^\ell\log\left(\frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right) - \gamma_i\sum_{s\in\mathcal{S}}\phi_i^s\log R_i^s\end{aligned}$$

or, in matrix notation,

$$\begin{aligned}\Big(I_{\mathcal{N}} - \operatorname{diag}(\mathbf{1}-\boldsymbol{\gamma})A - \sum_{s\in\mathcal{S}}\operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\phi}^s)\Omega^s\Big)(\log\boldsymbol{c} - \log\boldsymbol{\theta})\\ = \log\boldsymbol{z} + \log\boldsymbol{\mu} + \operatorname{diag}(\boldsymbol{\gamma})\boldsymbol{\phi}^\ell\log\left(\frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right) - \sum_{s\in\mathcal{S}}\operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\phi}^s)\log(\boldsymbol{R}^s).\end{aligned}$$

As a result,

$$\log\boldsymbol{c} = \log\boldsymbol{\theta} + (I_{\mathcal{N}}-\Gamma)^{-1}\left[\log\boldsymbol{z} + \log\boldsymbol{\mu} + \operatorname{diag}(\boldsymbol{\gamma})\boldsymbol{\phi}^\ell\log\left(\frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right) - \sum_{s\in\mathcal{S}}\operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\phi}^s)\log(\boldsymbol{R}^s)\right],$$

where $\Gamma \equiv \operatorname{diag}(\mathbf{1}-\boldsymbol{\gamma})A + \sum_s \operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\phi}^s)\Omega^s$. Aggregate consumption is $\log C = \boldsymbol{\theta}'\log\boldsymbol{c}$, thus,

$$\log C = \boldsymbol{\theta}'\log\boldsymbol{\theta} + \boldsymbol{\theta}'(I_{\mathcal{N}}-\Gamma)^{-1}\left[\log\boldsymbol{z} + \log\boldsymbol{\mu} + \operatorname{diag}(\boldsymbol{\gamma})\boldsymbol{\phi}^\ell\log\left(\frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right) - \sum_{s\in\mathcal{S}}\operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\phi}^s)\log(\boldsymbol{R}^s)\right]. \tag{B.27}$$

Counterfactuals with "exact-hat algebra". The tax shield impacts the economy through the rental rate of the different types of capital. Let $(R_i^s)'$ be the rental rate of type-s capital in sector i in the new equilibrium and let $\hat{R}_i^s \equiv (R_i^s)'/R_i^s$ be the change relative to the original equilibrium. We also assume $U(C) = C^{1-\sigma}/(1-\sigma)$ and $V(L) = L^{1+\epsilon}/(1+\epsilon)$. Using the "hat" notation we can rewrite (B.23) as

$$\hat{\ell}_i = \frac{\hat{C}^{1-\sigma}}{\hat{L}^\epsilon}\cdot\frac{\hat{y}_i}{\hat{c}_i}. \tag{B.28}$$

From labor-market clearing,

$$\hat{L} = \sum_{i\in\mathcal{N}} \frac{w\ell_i}{wL}\hat{\ell}_i$$

or, using (B.28),

$$\hat{L} = \frac{\hat{C}^{1-\sigma}}{\hat{L}^{\epsilon}} \sum_{i\in\mathcal{N}} \vartheta_i^L \frac{\hat{y}_i}{\hat{c}_i},$$

where $\vartheta_i^L \equiv w\ell_i/wL$. Similarly, we can rewrite (B.18) and (B.20) as

$$\hat{x}_{j,i} = \hat{y}_j \frac{\hat{c}_i}{\hat{c}_j} \tag{B.29}$$

and

$$\hat{i}_{j,i}^s = \frac{1}{\hat{R}_j^s}\hat{y}_j \frac{\hat{c}_i}{\hat{c}_j}, \tag{B.30}$$

respectively. Also, from (B.26), we obtain

$$\frac{\hat{k}_i^s}{\hat{y}_i} = \frac{1}{\hat{R}_i^s}\cdot\frac{1}{\hat{c}_i}\prod_{j\in\mathcal{N}} \hat{c}_j^{\omega_{ij}^s}. \tag{B.31}$$

The resource constraint (7) becomes

$$\hat{y}_i = \frac{p_i c_i}{p_i y_i}\hat{c}_i + \sum_{j\in\mathcal{N}} \frac{p_i x_{j,i}}{p_i y_i}\hat{x}_{j,i} + \sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}} \frac{p_i i_{j,i}^s}{p_i y_i}\hat{i}_{j,i}^s \tag{B.32}$$

or, using (B.18) and (B.20) with (B.29) and (B.30),

$$\frac{\hat{y}_i}{\hat{c}_i} = \vartheta_i^C + \sum_{j\in\mathcal{N}} \mu_j \alpha_{ji}(1-\gamma_j)\vartheta_{ji}^Y \frac{\hat{y}_j}{\hat{c}_j} + \sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}} \mu_j\gamma_j\phi_j^s\omega_{ji}^s \frac{\delta_j^s}{R_j^s}\vartheta_{ji}^Y \frac{1}{\hat{R}_j^s}\cdot\frac{\hat{y}_j}{\hat{c}_j}, \tag{B.33}$$

where we let $\vartheta_i^C \equiv p_i c_i/p_i y_i$ and $\vartheta_{ji}^Y \equiv p_j y_j/p_i y_i$.

Also, using (B.28), (B.29) and (B.31), we can rewrite (B.25) as

$$\hat{c}_i = \prod_{j\in\mathcal{N}} \hat{c}_j^{(1-\gamma_i)\alpha_{ij}} \left(\frac{\hat{C}^{1-\sigma}}{\hat{L}^{\epsilon}}\right)^{\gamma_i\phi_i^\ell} \prod_{s\in\mathcal{S}} \left(\frac{1}{\hat{R}_i^s}\prod_{j\in\mathcal{N}} \hat{c}_j^{\omega_{ij}^s}\right)^{\gamma_i\phi_i^s}$$

or, taking logs of both sides,

$$\log\hat{c}_i = \sum_{j\in\mathcal{N}}(1-\gamma_i)\alpha_{ij}\log\hat{c}_j + \gamma_i\phi_i^\ell \log\frac{\hat{C}^{1-\sigma}}{\hat{L}^{\epsilon}} - \sum_{s\in\mathcal{S}}\gamma_i\phi_i^s\log\hat{R}_i^s + \sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}}\gamma_i\phi_i^s\omega_{ij}^s\log\hat{c}_j. \tag{B.34}$$

Finally, from the definition of aggregate consumption,

$$\hat{C} = \prod_{i \in \mathcal{N}} \hat{c}_i^{\theta_i},$$

therefore,

$$\log \hat{C} = \sum_{i \in \mathcal{N}} \theta_i \log \hat{c}_i. \tag{B.35}$$

To sum up, the change in inputs, output and consumption in the counterfactual economy are the solution to equations (B.28), (B.29), (B.30), (B.31), (B.33), (B.34) and (B.35).

B.1 Proofs for Section 4.2

Let us define the firm's cost function:

$$\mathcal{C}^f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s, y_{i,t}^f) = \min_{\tilde{x}, \tilde{\ell}, \tilde{k}} \Big\{ \sum_{j \in \mathcal{N}} p_{j,t} \tilde{x}_{i,j,t}^f + w_t \tilde{\ell}_{i,t}^f + \sum_s R_{i,t}^s q_{i,t}^s \tilde{k}_{i,t}^{f,s} \Big\} + \tau_e e_i \tilde{y}_{i,t}^f,$$

subject to

$$y_{i,t}^f = \mathcal{F}_i(z_i, \{\tilde{x}_{i,j,t}^f\}_j, \tilde{\ell}_{i,t}^f, \{\tilde{k}_{i,t}^{f,s}\}_s).$$

Notice that, while we maintain the assumption of constant returns to scale, we do not restrict the production function to be Cobb-Douglas. The assumption of constant returns to scale implies

$$1 = \mathcal{F}_i\Big(z_i, \{\tilde{x}_{i,j,t}^f / y_{i,t}^f\}_j, \tilde{\ell}_{i,t}^f / y_{i,t}^f, \{\tilde{k}_{i,t}^{f,s} / y_{i,t}^f\}_s\Big),$$

for any value of $y_{i,t}^f$. It is thus sufficient to solve the problem for $y_{i,t}^f = 1$ and scale the resulting solution by $y_{i,t}^f$. Therefore, we have

$$\begin{aligned} \mathcal{C}^f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s, y_{i,t}^f) &= \Big(\sum_{j \in \mathcal{N}} p_{j,t} \chi_{i,j,t}^f + w_t \lambda_{i,t}^f + \sum_s R_{i,t}^s q_{i,t}^s \kappa_{i,t}^{f,s} + \tau_e e_i \Big) y_{i,t}^f \\ &\equiv \mathcal{MC}^f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s) y_{i,t}^f, \end{aligned}$$

where χ, λ and κ denote the solution to the firm's problem for $y_{i,t}^f = 1$, and $\mathcal{MC}^f$ is the firm's marginal cost curve. Homogeneity of the problem also implies that firm's optimal choices for any level of output $y_{i,t}^f$ (which we denote with $x_{i,j,t}^f$, $\ell_{i,t}^f$ and $k_{i,t}^{f,s}$) cam also be obtained by re-scaling their counterparts for $y_{i,t}^f = 1$, that is, $x_{i,j,t}^f = \chi_{i,j,t}^f y_{i,t}^f$, $\ell_{i,t}^f = \lambda_{i,t}^f y_{i,t}^f$ and $k_{i,t}^{f,s} = \kappa_{i,t}^{f,s} y_{i,t}^f$.

Given firm's cost function, the optimal price is the solution to the following problem:

$$\max_{\tilde{p}} (1 - \hat{\tau}_f) \tilde{p} y_{i,t}^f - \mathcal{C}^f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s, y_{i,t}^f),$$

subject to

$$y_{i,t}^{f} = \left(\frac{\tilde{p}}{p_{i,t}}\right)^{-\sigma_i} y_{i,t}. \tag{B.36}$$

Notice that we also allow for a firm-specific revenue tax $\hat{\tau}_f$ (a subsidy, if negative).

The first-order condition is

$$(1-\hat{\tau}_f)\left(\frac{p_{i,t}^{f}}{p_{i,t}}\right)^{-\sigma_i} y_{i,t} - (1-\hat{\tau}_f)\sigma_i\left(\frac{p_{i,t}^{f}}{p_{i,t}}\right)^{-\sigma_i} y_{i,t} + \sigma_i \mathcal{MC}^f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s)\frac{1}{p_{i,t}^{f}}\left(\frac{p_{i,t}^{f}}{p_{i,t}}\right)^{-\sigma_i} y_{i,t} = 0$$

or, rearranging,

$$(1-\hat{\tau}_f)p_{i,t}^{f} = \frac{1}{\mu_i}\mathcal{MC}^f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s). \tag{B.37}$$

Taking the logarithm of the price equation (B.37) and differentiating it with respect to $R_{i,t}^{s}$ gives

$$\frac{\partial \log p_{i,t}^{f}}{\partial R_t^s} = \frac{1}{p_{i,t}^{f}} \cdot \frac{1}{\mu_i(1-\hat{\tau}_f)} \cdot \frac{\partial \mathcal{MC}^f}{\partial R_{i,t}^{s}}.$$

To compute the derivative of the marginal cost, we apply the envelope theorem to the cost function:

$$\frac{\partial \mathcal{C}^f}{\partial R_{i,t}^{s}} = y_{i,t}^{f}\frac{\partial \mathcal{MC}^f}{\partial R_{i,t}^{s}} = q_{i,t}^{s} k_{i,t}^{f,s}.$$

We conclude that

$$\frac{\partial \log p_{i,t}^{f}}{\partial R_{i,t}^{s}} = \frac{1}{\mu_i(1-\hat{\tau}_f)} \cdot \frac{q_{i,t}^{s} k_{i,t}^{f,s}}{p_{i,t}^{f} y_{i,t}^{f}}. \tag{B.38}$$

Having computed the percentage change in price, we can compute the percentage change in firm's emissions $\partial \log E_{i,t}^{f}/\partial R_{i,t}^{s}$. Since $E_{i,t}^{f} = e_i y_{i,t}^{f}$, the latter is the same as the percentage change in output $\partial \log y_{i,t}^{f}/\partial R_{i,t}^{s}$. Using the demand equation (B.36), we have

$$\frac{\partial \log y_{i,t}^{f}}{\partial R_{i,t}^{s}} = -\sigma_i \frac{\partial \log p_{i,t}^{f}}{\partial R_{i,t}^{s}}. \tag{B.39}$$

Consider now the no-tax-shield policy. As discussed in the main text, such policy implies a change in the rental rate of type-s capital equal to $\Delta R_{i,t}^{s} = \tau_p/(1-\tau_p) r_{i,t}^{b} \psi_{i,s}/(1+r_{i,t}^{b})$. Combining (B.38) and (B.39) yields the total differential

$$d\log E_{i,t}^{f} = -\sigma_i \frac{1}{\mu_i(1-\hat{\tau}_f)} \sum_{s\in\mathcal{S}} \frac{q_{i,t}^{s} k_{i,t}^{f,s}}{p_{i,t}^{f} y_{i,t}^{f}} \cdot \frac{\tau_p}{1-\tau_p} r_{i,t}^{b} \frac{\psi_{i,s}}{1+r_{i,t}^{b}}. \tag{B.40}$$

In steady state, the latter coincides with (17).

Analogous steps prove that

$$\frac{\partial \log p_{i,t}^f}{\partial \tau_e} = \frac{1}{\mu_i(1-\hat{\tau}_f)} \cdot \frac{E_{i,t}^f}{p_{i,t}^f y_{i,t}^f}$$

and, thus,

$$d\log E_{i,t}^f = -\sigma_i \frac{1}{\mu_i(1-\hat{\tau}_f)} \cdot \frac{E_{i,t}^f}{p_{i,t}^f y_{i,t}^f}\tau_e, \tag{B.41}$$

which becomes (18) in steady state.

We are left to prove the equivalence between the tax shield policy and a policy comprising a carbon tax and a revenue tax. To simplify notation, we focus directly on steady-state variables and drop time subscripts. First, notice that differentiating (B.37) with respect to $\hat{\tau}_f$ gives the price effect of a change in the revenue tax:

$$\frac{\partial \log p_i^f}{\partial \hat{\tau}_f} = \frac{1}{1-\hat{\tau}_f}.$$

As a result, the total change in emissions following the introduction of a revenue tax is

$$d\log E_i^f = -\sigma_i \frac{\hat{\tau}_f}{1-\hat{\tau}_f}. \tag{B.42}$$

Second, using the fact that the borrowing constraint (B.11) holds with equality, we have that

$$\sum_{s\in\mathcal{S}} q_i^s k_i^{f,s} \frac{\tau_p}{1-\tau_p} r_i^b \frac{\psi_{i,s}}{1+r_i^b} = \frac{\tau_p}{1-\tau_p} r_i^b b_i^f \equiv \frac{1}{1-\tau_p} TS_i^f,$$

where the last line uses the definition of tax shield given in the main text. It follows that we can rewrite (B.40) as

$$d\log E_i^f = -\sigma_i \frac{1}{\mu_i(1-\hat{\tau}_f)(1-\tau_p)} \cdot \frac{TS_i^f}{p_i^f y_i^f}$$

or, using the decomposition (19),

$$d\log E_i^f = -\sigma_i \frac{1}{\mu_i(1-\hat{\tau}_f)(1-\tau_p)} \Big(\beta \frac{E_i^f}{p_i^f y_i^f} + \epsilon_i^f\Big).$$

Finally, using (B.41) and (B.42), the latter gives the effect of a policy mix comprising a carbon tax $\tau_e = \beta/(1-\tau_p)$ and a second-specific revenue tax $\hat{\tau}_f = \epsilon_i^f/\mu_i(1-\tau_p)$.

B.2 Extension to CES Production

We begin with consumption. As in the baseline case, we minimize total expenditures

$$\sum_{i\in\mathcal{N}}\int p_{i,t}^{f}c_{i,t}^{f}df,$$

subject to achieving some level of aggregate consumption

$$C_t\equiv\left((1-\eta)\left(\prod_{i\neq\bar{j}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\right)+\eta(c_{\bar{j},t})^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}},\tag{B.43}$$

where consumption on goods from sector i is $c_{i,t}\equiv\left(\int(c_{i,t}^{f})^{\frac{\sigma_i-1}{\sigma_i}}df\right)^{\frac{\sigma_i}{\sigma_i-1}}$. As in the baseline case, we obtain the demand schedule (B.1).

We are left to find the optimal level of $c_{i,t}$. Letting λ_t be the Lagrange multiplier on (B.43), the first-order condition for $i\neq\bar{j}$ is

$$(1-\eta)\theta_i C_t^{\frac{1}{\rho}}\left(\prod_{i\neq\bar{j}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\right)^{\frac{\rho-1}{\rho}}=(1+\tau_c)\lambda_t p_{i,t}c_{i,t}.\tag{B.44}$$

Similarly, the first-order condition for $\bar{j}$ is

$$\eta C_t^{\frac{1}{\rho}}(c_{\bar{j},t})^{\frac{\rho-1}{\rho}}=(1+\tau_c)\lambda_t p_{\bar{j},t}c_{\bar{j},t}.\tag{B.45}$$

Summing (B.44) over $i\neq\bar{j}$,

$$(1-\eta)C_t^{\frac{1}{\rho}}\left(\prod_{i\neq\bar{j}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\right)^{\frac{\rho-1}{\rho}}=(1+\tau_c)\lambda_t\sum_{i\neq\bar{j}}p_{i,t}c_{i,t}$$

Summing the latter with (B.45) gives

$$(1+\tau_c)\lambda_t\sum_{i\in\mathcal{N}}p_{i,t}c_{i,t}=(1-\eta)C_t^{\frac{1}{\rho}}\left(\prod_{i\neq\bar{j}}c_{i,t}^{\theta_i}\right)^{\frac{\rho-1}{\rho}}+\eta C_t^{\frac{1}{\rho}}(c_{\bar{j},t})^{\frac{\rho-1}{\rho}}$$

or

$$(1+\tau_c)\lambda_t\sum_{i\in\mathcal{N}}p_{i,t}c_{i,t}=C_t.\tag{B.46}$$

From (B.44),

$$\frac{c_{i,t}}{\theta_i}=\frac{1}{(1+\tau_c)\lambda_t p_{i,t}}(1-\eta)C_t^{\frac{1}{\rho}}\left(\prod_{i\neq\bar{j}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\right)^{\frac{\rho-1}{\rho}}$$

Raising the latter to the power of θ_i, multiplying for all $j \neq \bar{j}$ and rearranging, we obtain

$$\left(\prod_{i\neq\bar{j}}\left(\frac{c_{i,t}}{\theta_i}\right)^{\theta_i}\right)^{\frac{1}{\rho}} = \frac{1}{(1+\tau_c)\lambda_t}C_t^{\frac{1}{\rho}}\prod_{i\neq\bar{j}}(1-\eta)^{\theta_i}p_{i,t}^{-\theta_i}. \tag{B.47}$$

Similarly, from (B.45),

$$c_{\bar{j},t}^{\frac{1}{\rho}} = \frac{1}{(1+\tau_c)\lambda_t}\eta C_t^{\frac{1}{\rho}}p_{\bar{j},t}^{-1}. \tag{B.48}$$

Raising both (B.47) and (B.48) to the power of $\rho-1$ and using them with the definition of aggregate consumption (B.43) yields

$$(1+\tau_c)\lambda_t = \left((1-\eta)\prod_{i\neq\bar{j}}(1-\eta)^{(\rho-1)\theta_i}p_{i,t}^{(1-\rho)\theta_i} + \eta(\eta)^{\rho-1}p_{\bar{j},t}^{1-\rho}\right)^{\frac{1}{1-\rho}} \equiv P_t, \tag{B.49}$$

where the right-hand-side is the appropriate price level, which we normalize to one. Combining (B.46) with (B.49) implies

$$\sum_{i\in\mathcal{N}} p_{i,t}c_{i,t} = C_t.$$

Also, using (B.49) with (B.44) and (B.45) yields, respectively,

$$c_{i,t} = \frac{1}{p_{i,t}}\theta_i(P^{C\setminus E})^{1-\rho}(1-\eta)C_t$$

and

$$c_{\bar{j},t} = \frac{1}{p_{\bar{j},t}^{\rho}}\eta^{\rho}C_t,$$

where

$$P_t^{C\setminus E} \equiv \prod_{i\neq\bar{j}}(1-\eta)^{-\theta_i}p_{i,t}^{\theta_i}$$

is the price of the consumption bundle excluding the energy sector.

Evaluating those conditions in a symmetric steady state and using the "hat" notation, we finally obtain:

$$\hat{c}_i = \frac{1}{\hat{p}_i}(\hat{P}^{C\setminus E})^{1-\rho}\hat{C} \tag{B.50}$$

and

$$\hat{c}_{\bar{j}} = \frac{1}{\hat{p}_{\bar{j}}^{\rho}}\hat{C}, \tag{B.51}$$

where $\hat{P}^{C\setminus E} = \prod_{i\neq\bar{j}}\hat{p}_i^{\theta_i}$.

We now turn to the firm's problem, which coincides with the one in the baseline case except for the different production function. Formally, the firm maximizes $\mathbb{E}\sum_{t=0}^{\infty}\varphi_t d_{i,t}^{f}$, subject to (B.6), (B.9)-(B.12), and

$$\hat{y}^f_{i,t} = \mathcal{F}_i\Big(\{\hat{x}^f_{i,j,t}\}_j, \hat{\ell}^f_{i,t}, \{\hat{k}^{f,s}_{i,t}\}_s\Big), \tag{B.52}$$

where $\mathcal{F}_i$ is given by (20). As already explained in the main text, for convenience we are defining the production function directly in terms of deviations from a baseline equilibrium. Thus, for example, we let $\hat{y}^f_{i,t} \equiv (y^f_{i,t})'/y^f_{i,t}$, where variables with a prime are evaluated in the new equilibrium, while those without a prime are evaluated in the baseline equilibrium. The firm optimizes over the following variables: $(p^f_{i,t})'$, $(y^f_{i,t})'$, $(\ell^f_{i,t})'$, $(i^{f,s}_{i,j,t})'$, $(I^{f,s}_{i,t})'$, $(k^{f,s}_{i,t+1})'$, $(x^f_{i,j,t})'$ and $(b^f_{i,t+1})'$.

The optimal choice of labor satisfies the first-order condition

$$\mu_i\gamma_i\phi^\ell_i(p^f_{i,t})'y^f_{i,t}\hat{a}^f_{i,t} = w'_t(\ell^f_{i,t})',$$

where we have defined $\hat{a}^f_{i,t} \equiv (\hat{y}^f_{i,t})^{\frac{1}{\varsigma}}(\widehat{VA}^f_{i,t})^{1-\frac{1}{\varsigma}}$. Dividing the latter by its counterpart in the baseline equilibrium (where labor satisfies the first-order condition $\mu_i p^f_{i,t}\gamma_i\phi^\ell_i y^f_{i,t} = w_t\ell^f_{i,t}$) we have

$$\hat{p}^f_{i,t}\hat{a}^f_{i,t} = \hat{w}_t\hat{\ell}^f_{i,t}. \tag{B.53}$$

Conditional on total investment $I^{f,s}_{i,t}$, the choice of $i^{s,f}_{i,j,t}$ is the same as in the baseline equilibrium, therefore, equation (B.15) continues to hold. Instead, the optimal choice of capital now satisfies

$$\mu_i\gamma_i\phi^s_i(p^f_{i,t})'y^f_{i,t}\hat{a}^f_{i,t} = (R^s_{i,t})'(q^s_{i,t})'(k^{f,s}_{i,t})',$$

where the rental rate is given by (B.17). Dividing the latter by its counterpart in the baseline equilibrium yields

$$\hat{p}^f_{i,t}\hat{a}^f_{i,t} = \hat{R}^s_{i,t}\hat{q}^s_{i,t}\hat{k}^{f,s}_{i,t}. \tag{B.54}$$

Evaluating (B.53) and (B.54) in a symmetric steady state, we obtain

$$\frac{\hat{w}\hat{\ell}_i}{\hat{p}_i\hat{a}_i} = 1 \qquad \text{and} \qquad \hat{R}^s_i\frac{\hat{q}^s_i\hat{k}^s_i}{\hat{p}_i\hat{a}_i} = 1.$$

Finally, evaluating (B.15) in a symmetric steady state and using the fact that investment must satisfy $I^s_i = \delta^s_i k^s_i$, which implies $\hat{I}^s_i = \hat{k}^s_i$, we have

$$\hat{i}^s_{i,j} = \frac{1}{\hat{p}_j\hat{R}^s_i}\hat{p}_i\hat{a}_i. \tag{B.55}$$

Consider now the first-order condition with respect to the input demand for sector $\bar{j}$'s product:

$$\mu_i(1-\gamma_i)\eta_i(p^f_{i,t})'y^f_{i,t}(\hat{y}^f_{i,t})^{\frac{1}{\varsigma}}\left(\hat{X}^f_{i,t}\right)^{\frac{1}{\rho}-\frac{1}{\varsigma}}(\hat{x}^f_{i,\bar{j},t})^{\frac{\rho-1}{\rho}} = p'_{\bar{j},t}(x^f_{i,\bar{j},t})'.$$

Dividing the latter by its counterpart in the baseline equilibrium, we obtain

$$\hat{p}^f_{i,t}(\hat{y}^f_{i,t})^{\frac{1}{\varsigma}}\left(\hat{X}^f_{i,t}\right)^{\frac{1}{\rho}-\frac{1}{\varsigma}} = \hat{p}_{\bar{j},t}(\hat{x}^f_{i,\bar{j},t})^{\frac{1}{\rho}}.$$

In a symmetric state state,

$$\hat{x}_{i,\bar{j}} = \hat{p}_i^{\rho}\hat{y}_i^{\frac{\rho}{\varsigma}}\hat{X}_i^{1-\frac{\rho}{\varsigma}}\hat{p}_{\bar{j}}^{-\rho}. \tag{B.56}$$

Finally, the first-order condition with respect to the input demand for the good produced by any sector $j \neq \bar{j}$ is

$$\mu_i(p^f_{i,t})'y^f_{i,t}(1-\gamma_i)(1-\eta_i)(\hat{y}^f_{i,t})^{\frac{1}{\varsigma}}\left(\hat{X}^f_{i,t}\right)^{-\frac{1}{\varsigma}}\left(\hat{X}^f_{i,t}\right)^{\frac{1}{\rho}}\left(\prod_{j\neq\bar{j}}(\hat{x}^f_{i,j,t})^{\alpha_{ij}}\right)^{\frac{\rho-1}{\rho}} = p'_{j,t}(x^f_{i,j,t})'$$

or, dividing by the baseline equilibrium and evaluating the resulting expression in a symmetric state state,

$$\hat{x}_{i,j} = \hat{p}_i\hat{y}_i^{\frac{1}{\varsigma}}\hat{X}_i^{\frac{1}{\rho}-\frac{1}{\varsigma}}\left(\prod_{j\neq\bar{j}}\hat{x}_{i,j}^{\alpha_{ij}}\right)^{\frac{\rho-1}{\rho}}\hat{p}_j^{-1}. \tag{B.57}$$

Raising (B.57) to the power of α_{ij} and multiplying over $j \neq \bar{j}$ yields

$$\prod_{j\neq\bar{j}}\hat{x}_{i,j}^{\alpha_{ij}} = \hat{p}_i^{\rho}\hat{y}_i^{\frac{\rho}{\varsigma}}\hat{X}_i^{1-\frac{\rho}{\varsigma}}\prod_{j\neq\bar{j}}(\hat{p}_j)^{-\rho\alpha_{ij}}. \tag{B.58}$$

Raising both sides of (B.56) and (B.58) to the power of $(\rho-1)/\rho$, and taking a weighted average of the two conditions (with weights η_i and $(1-\eta_i)$, respectively) gives

$$\hat{X}_i^{\frac{\rho-1}{\varsigma}} = \hat{p}_i^{\rho-1}\hat{y}_i^{\frac{\rho-1}{\varsigma}}\left((1-\eta_i)\prod_{j\neq\bar{j}}\hat{p}_j^{(1-\rho)\alpha_{ij}} + \eta_i\hat{p}_{\bar{j}}^{1-\rho}\right).$$

Raising the latter to the power of $(\varsigma-\rho)/(\rho-1)$, substituting it back into (B.56) and (B.57), and rearranging yields, respectively, the demand for sector $\bar{j}$'s good:

$$\hat{x}_{i,\bar{j}} = \hat{p}_i^{\varsigma}\hat{y}_i\left((1-\eta_i)\prod_{j\neq\bar{j}}\hat{p}_j^{(1-\rho)\alpha_{ij}} + \eta_i\hat{p}_{\bar{j}}^{1-\rho}\right)^{\frac{\varsigma-\rho}{\rho-1}}\hat{p}_{\bar{j}}^{-\rho}; \tag{B.59}$$

and the demand for the good produced by any sector $j \neq \bar{j}$:

$$\hat{x}_{i,j} = \hat{p}_i^{\varsigma}\hat{y}_i\left((1-\eta_i)\prod_{j\neq\bar{j}}\hat{p}_j^{(1-\rho)\alpha_{ij}} + \eta_i\hat{p}_{\bar{j}}^{1-\rho}\right)^{\frac{\rho-\varsigma}{1-\rho}}\left(\prod_{j\neq\bar{j}}\hat{p}_j^{(1-\rho)\alpha_{ij}}\right)\hat{p}_j^{-1}. \tag{B.60}$$

Raising the latter to the power of α_{ij} and multiplying across $j \neq \bar{j}$ gives

$$\prod_{j\neq\bar{j}} \hat{x}_{i,j}^{\alpha_{ij}} = \hat{p}_i^{\varsigma} \hat{y}_i \left((1-\eta_i) \prod_{j\neq\bar{j}} \hat{p}_j^{(1-\rho)\alpha_{ij}} + \eta_i \hat{p}_{\bar{j}}^{1-\rho} \right)^{\frac{\rho-\varsigma}{1-\rho}} \prod_{j\neq\bar{j}} (\hat{p}_j)^{-\rho\alpha_{ij}}.$$

We can then substitute the latter expressions into the production function and rearrange to obtain

$$\hat{p}_i^{1-\varsigma} = \gamma_i \big(\widehat{P}_i^{VA}\big)^{1-\varsigma} + (1-\gamma_i)\big(\hat{P}_i^{X}\big)^{1-\varsigma}. \tag{B.61}$$

where we have defined

$$\widehat{P}_i^{VA} \equiv \hat{w}^{\phi_i^{\ell}} \prod_{s\in\mathcal{S}} \left(\left(\hat{R}_i^s\right)^{\phi_i^s} \prod_{j\in\mathcal{N}} \hat{p}_j^{\phi_i^s \omega_{ij}^s} \right)$$

and

$$\hat{P}_i^{X} \equiv \left((1-\eta_i) \prod_{j\neq\bar{j}} \hat{p}_j^{(1-\rho)\alpha_{ij}} + \eta_i \hat{p}_{\bar{j}}^{1-\rho} \right)^{\frac{1}{1-\rho}}.$$

Equation (B.61) can be used to solve for $\{\hat{p}_i\}$, for given $\hat{w}$ and $\{\hat{R}_i^s\}$. Given prices, we can use (B.50) and (B.51) together with (B.35) to obtain consumption $\hat{c}_i$, for given prices and aggregate consumption. Finally, output $\hat{y}_i$ comes from the resource constraint (B.32), combined with demand functions (B.50), (B.51), (B.55), (B.59) and (B.60).