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 find that dirty firms pay lower profit taxes—the opposite of what optimal taxation of negative externalities prescribes. 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 embed our estimates into a general-equilibrium framework and show that eliminating the tax-advantage of debt reduces carbon emissions by about 6.1%, while aggregate output falls by roughly 3%. Finally, we show that a properly designed policy achieves a fall in total emissions of roughly 2% without any noticeable change in GDP.

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1 Introduction

Carbon dioxide (CO_2) emissions represent the quintessential negative externality. A central tenet of economic theory is that individual decisions tend to be inefficient in the presence of externalities: left free to pollute, households and firms are likely to cause environmental damage and welfare loss. The classical response to restore efficiency is to impose a Pigouvian tax on carbon emissions or an equivalent quantity-capping mechanism, such as a cap-and-trade market. A well-designed policy re-aligns the price of carbon emissions with their social cost.

In practice, currently only 20% of global carbon emissions are covered by some form of climate-change regulation (World Bank, 2018), and even in the regions where regulation exists carbon prices are typically well below the estimated social cost. To make things worse, researchers and policymakers typically argue that optimal regulation requires a global coordination. A local intervention, the argument goes, would only reduce the competitiveness of domestic energy-intensive industries, pushing firms to relocate to less regulated regions, without any sizable reduction in global emissions.

Carbon bias of corporate taxation. In the absence of an explicit tax on carbon emissions, tax codes may still discourage pollution by taxing it indirectly. For example, if polluting firms are capital intensive, then a tax on capital will also be an implicit tax on pollution. In this paper, we document that this is not the case. In fact, we find the opposite: Dirty firms pay, on average, *lower* taxes. Thus, our analysis shows that corporate taxes *subsidize* pollution.

To reach this conclusion, we relate profit taxes to carbon intensity. Our analysis focuses on the U.S., from 2004 to 2019. We obtain 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 (scaled by sales) on carbon emissions (also scaled by sales) in the cross-section of firms. We find that 1 tonne of carbon is associated with around 5 USD lower taxes.

The mechanism. Having documented a negative relationship between corporate taxes and carbon emissions, we turn to its determinants. We show that it 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 tax shield that a firm enjoys is thus given by the firm's interest expenses multiplied by the statutory corporate tax rate faced by the firm depending on the (domestic and 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.[1]

Why is it that dirty firms can take more advantage of the tax shield of debt? Dirty firms, our analysis shows, tend to have a higher leverage (i.e. debt over sales). 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 statutory tax rates, it follows that dirty firms' higher tax shield—and the negative relationship between taxes and carbon emissions—is fully accounted by the higher leverage of these firms. Thus, 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 shows that asset tangibility is the key driver of differences in borrowing across firms. The fact that firms with more tangible assets can sustain a higher leverage is consistent with a large body of work in corporate finance studying the determinants of leverage across firms, industries and countries (see, e.g., Titman and Wessels (1988) and Rajan and Zingales (1995)). The novelty of our analysis is to uncover the strong positive correlation between asset tangibility and carbon emissions: Dirty firms own more tangible assets on average. 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, results hold also for private firms and in sub-samples of domestic versus multinational firms. Results 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

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

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.

Our estimates are economically large. To appreciate their economic significance 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 governments worldwide in a given year. Our analysis, therefore, uncovers a quantitatively important channel through which corporate taxation impacts carbon emissions—a channel that has been so far overlooked both in the academic literature and by policymakers.

The model. 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 is 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 allowing firms to ameliorate the asymmetric information problem. Finally, the model must consider general-equilibrium forces: taking into account the endogenous response of all prices is crucial to assess the implications of economy-wide policy changes.

We also incorporate a rich input/output network structure into the model. This is a key ingredient in a model in which carbon intensity varies across industries. 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 will lead us to an incorrect inference about the effects of policy reforms aimed at reducing carbon emissions. More specifically, we consider two types of input/output networks. The first one is the standard intermediate-goods network: firms in any given sector require output from all other sectors. The second network is, instead, less common: we assume that capital goods are produced by combining goods from all sectors. This is known as the "investment network" (Lehn and Winberry, 2020). What is more, we extend the analysis in Lehn and Winberry (2020) to three different types of capital (i.e., structures, equipment and intangibles) and assume a different investment network for each one of them.

Policy counterfactuals. In our main policy counterfactual we study a tax reform which forbids firms from deducting interest expenses. The policy raises firms' user cost of capital, prompting them 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, 3.01% and 2.39% lower. The reduction in aggregate output is accompanied by a decrease in total emissions of 6.08%.

The reason for the large fall in emissions—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 is removed, firms in dirty industries experience a relatively higher increase in the user cost of (tangible) capital and, as 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 once the tax shield is removed. This correlation is responsible for the substantial decrease in total emissions.

We compare the no-tax-shield policy to a carbon tax, arguably the best-known policy to reduce carbon emissions. We show that a carbon tax of USD 26.72 achieves the same fall in carbon emissions, but with a smaller drop in output and consumption. The model, it turns out, offers a neat way to compare the two policies. In particular, we derive a decomposition in which the no-tax-shield policy is equivalent to a combination of two taxes: a carbon tax and a firm-specific revenue tax. By impacting firms in a way that is unrelated to carbon emissions, the revenue-tax component is responsible for the less targeted nature of the no-tax-shield policy, and ultimately for the larger drop in output and consumption.

A policy that removes the tax advantage of debt essentially increases taxes on the corporate sector. The government budget is thus affected, and so are GDP and household consumption. In our last counterfactual, we show that the government can 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 subsidy—can achieve a fall in total emissions of roughly 2% without any noticeable change in GDP. The reason lies, once again, in the fact that the policy mix can alter the composition of aggregate production in favor of cleaner industries.

Related literature. To the best of our knowledge, this paper is the first to document an association between corporate taxation and firms' carbon emissions, and the first that quantifies the environmental consequences of counterfactual corporate taxation systems. To that end, we combine insights from the theoretical literature on environmental economics (Bovenberg and Goulder, 1996; Acemoglu, Aghion, Bursztyn, and Hémous, 2012; Golosov, Hassler, Krusell, and Tsyvinski, 2014) with the production network literature (Liu, 2019; Baqaee and Farhi, 2020; 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.

Our findings contribute to a large body of empirical work on the environmental consequences of taxation, such as carbon taxes (see 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). Sanati (2017); Carrizosa, Gaertner, and Lynch (2020) estimate the effects of the limitation on the interest payments' deductibility introduced in 2017 in the U.S. on firm leverage, investment, and employment.[2] We are to the best of our knowledge the first paper to focus on

[2] 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 consequences of corporate taxation, and the debt tax shield, 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 our case, we hold corporate taxation fixed and explore in counterfactuals the consequences of removing the tax advantage of debt for the environment.

We also add to a fast growing literature in climate finance (see e.g. Giglio, Kelly, and Stroebel, 2021, for a review). A series of recent work in asset pricing studies the role of financial markets in affecting the cost of capital of clean versus dirty firms. In that vein, Bolton and Kacperczyk (2021b), Bolton and Kacperczyk (2021c) and Hsu, Li, and Tsou (2020) estimate the risk premium on stocks associated to firms' carbon and toxic emissions, Ilhan, Sautner, and Vilkov (2021) relate firms' carbon emissions to the pricing of downside tail risk in option markets, whereas Baker, Bergstresser, Serafeim, and Wurgler (2022) and Zerbib (2019) focus on the pricing of green bonds. Piazessi, Papoutsi, and Schneider (2021) show that ECB bond purchases favor firms with more tangible capital and carbon emissions. Bolton and Kacperczyk (2021a) find that carbon emissions disclosure lowers firms' cost of capital. Chava (2014) document that firms with poor environmental policies have higher cost of capital. Other work in corporate finance sheds light on a series of determinants of firms' pollution, such as limited liability (Akey and Appel, 2020), mandatory carbon disclosure (Jouvenot and Krueger, 2021), countries' financial development (De Haas and Popov, 2020), financial constraints (Kim and Xu, 2021; Bartram, Hou, and Kim, 2022), ownership structure (Shive and Forster, 2020), institutional ownership (Dyck, Lins, Roth, and Wagner, 2019), and investors' activism (Akey and Appel, 2021). Compared to these papers, our contribution is to study the consequences of the tax advantage of debt for carbon emissions.

Our work has important policy implications. While a Pigouvian tax on all carbon emissions would be an efficient solution to address climate change, its implementation is facing significant political constraints.[3] In a world with or without carbon tax, our results indicate that corporate taxation acts today indirectly as an important subsidy on firms' carbon emissions, and as such

the effects of other types of taxes (such as dividend tax), or tax incentives (such as bonus depreciation), on firms' outcomes.

[3]See for instance Klenert, Mattauch, Combet, Edenhofer, Hepburn, Rafaty, and Stern (2018) for a review of the political obstacles to environmental policies, and Douenne and Fabre (Forthcoming) for survey evidence on individuals' negative attitudes towards carbon pricing in France.

matters for climate change. Previous work have discussed the distortions driven by the differential tax treatment of debt versus equity (e.g Stiglitz, 1973; King, 1974; Boadway and Bruce, 1984; Devereux and Freeman, 1991). In that vein, we are the first paper to show that the current tax advantage of debt financing over equity financing is implicitly subsidizing pollution, and to quantify the environmental consequences of harmonizing the tax treatment of debt and equity in a general-equilibrium model. In that respect, our work suggests that the design of corporate taxation might be a relevant policy instrument for affecting global carbon emissions, and is informative about the consequences of recent tax reforms.[4]

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 2019 – instead levy 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.

Debt tax shield. The federal tax code allows C corporations to deduct interest payments from their profits. Instead, dividends paid to shareholders are not deductible. The tax deductibility of interest payments exists in corporate taxation schemes in virtually all countries. Some countries introduced an Allowance for Corporate Equity (such as Croatia 1994, Brazil 1996, Italy 1997, Austria 2000, Belgium 2006 and Portugal 2010), which consists in granting to equity a similar tax deductibility than to debt. Moreover, several countries have introduced measures that put a cap on interest deductibility, often called thin capitalisation rules or income stripping rules. For instance,

[4]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.

[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.

in the United States from 2018, Section 163(j) of the Internal Revenue Code limits interest expense to 30 percent of a group's earnings before interest, taxes, depreciation and amortization (EBITDA) for firms above a certain size threshold.[6]

The reasons for why the debt tax subsidy was initially implemented are unclear. De Mooij (2012) notes that the original rationale to allow a deduction for debt 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 reflected in the tax code, which allows interest payments to be deductible for the corporate income tax as a cost, unlike equity returns.[7]

The debt tax shield 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 equal to around 10% of firm value. Despite its importance in the real world, the economic rationale for the existence of the tax shield is unclear. From an economic point of view, both interest and equity payments represent a return to capital and there are no obvious reasons ex ante for why one should be taxed at a different rate than the other. 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] The debt tax shield can also 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, being a tax on the return of capital, depresses

[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 associated to the debt tax shield increases firms' incentives to exit, which, although costly for the firm, is socially beneficial. More generally, debt financing can result in positive externalities through 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 of removing the debt tax shield for the environment.

the demand for capital in the corporate sector, and in turn reduces firms' incentives to invest. In general equilibrium, when two firms are taxed at different effective rates, the more heavily taxed firms tend to shrink and the less heavily taxed firms tend to expand. Even though two firms in the same location typically face similar statutory tax rates, a series of tax deductions can lead some firms to pay less taxes than others, depending for instance on the type of assets they acquire, and the way they finance their activities. Given that certain types of capital are cheaper to finance with debt than others, the debt tax shield acts as a larger subsidy on some types of capital than others. In particular, investments in tangible capital, such as machinery and equipment, can sustain higher leverage ratios, and therefore have lower post-tax cost of capital than investments 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 targeted tax incentives in specific 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 take into account the implications of their incidence on firms in our empirical and theoretical analysis.

3 Empirical Evidence

3.1 Data

We combine five main sources of data: firms' financial information from Compustat Northamerica Fundamentals, firms' carbon emissions from Trucost, the location of firms' heaquarters and establishments within the U.S. from Infogroup, the location of U.S. multinationals' activities across countries from Factset, and statutory corporate tax rates across U.S. states and across countries from the Tax Foundation. We present them in turn.

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

3.1.1 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.

3.1.2 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 firms with non-missing emissions data in Trucost in a given year. As shown in Figure A.1, coverage in Trucost has increased over time. In 2018, we observe carbon emissions for around 65% of Compustat firms, which represent more than 80% 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]

[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). Correlations 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). In untabulated tests we confirm that our baseline results hold when using data from Thomson & Reuters instead.

[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.

3.1.3 Location of Firms' Operations and Firm-level Tax Rates

Infogroup. We exploit information gathered by Infogroup to identify firms' headquarter state location as well as the employment and sales for each of their domestic establishments. In our sample, 45% of firms' U.S. employees are located in different states than firms' headquarters. Infogroup contacts establishments by phone and collects data, among other things, on sales and the number of full-time equivalent employees.[13]

Factset. We use Factset to obtain the distribution of U.S. multinationals' foreign sales across countries. This is another important source of information for our purposes given that firms in our sample realize around 25% of their sales abroad. Together with information on the domestic location of firms' activities from Infogroup, this allows us to measure properly the average statutory tax rate that each firm faces depending on the location of its operations both across States within the U.S. and across foreign countries for U.S. firms with activities abroad.

U.S. States and international corporate tax data. For state-level corporate tax records, 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. Firms are taxed in every state in which they have a physical presence. Most states tax corporate activities through profits. The exceptions, as of 2021, are Nevada, Ohio, Texas, and Washington, which levy a gross receipts tax based upon firms' revenues rather than income; importantly for our purposes, in these states interest expenses are not tax-deductible. We complement the data with similar corporate tax records for each foreign country. The data covers the same sample period and is also obtained from the Tax Foundation. Finally, we use the data shared by Giroud and Rauh (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.

Firm-level exposure to corporate tax rates and the value of the tax shield. To construct a precise measure of corporate tax rates at the firm level, we first exploit information from Infogroup

[13] 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.

on employment counts (denoted Emp below), sales and state location of firms' establishments within the U.S. Formally, let us define the domestic tax weights of U.S. state s in year t for firm f:

$$\omega_{s,t}^{f,US} = (1-\alpha_{s,t}^{Sales}) \cdot \frac{Emp_{s,t}^{f,US}}{\sum_{s\in US} Emp_{s,t}^{f,US}} + \alpha_{s,t}^{Sales} \cdot \frac{Sales_{s,t}^{f,US}}{\sum_{s\in US} Sales_{s,t}^{f,US}}, \tag{1}$$

with $\alpha_{s,t}^{Sales}$ being the apportionment factors on sales in state s and year t. Equation 2 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 $\omega_{s,t}^{f,US}$ across U.S. states is not necessarily equal to 1 because sales apportionment factors are heterogeneous across states.[14]

Similarly, we use information from Factset on sales by country of U.S. multinationals, if any. Formally, for firms with positive foreign sales, let us define the weight of country c in the foreign sales of firm f in year t:

$$\omega_{c,t}^{f,Foreign} = \frac{Sales_{c,t}^{f,Foreign}}{\sum_{c\notin US} Sales_{c,t}^{f,Foreign}}, \tag{2}$$

with $\sum_{c\notin US} \omega_{c,t}^{f,Foreign} = 1$.

We then compute the weighted-average statutory tax rate that U.S. firms face in each year using the following formula:

$$\tau_{f,t} = \omega_{US,t}^{f} \cdot (\tau_{fed,t} + \sum_{s} \omega_{s,t}^{f} \cdot \tau_{s,t}) + (1-\omega_{US,t}^{f}) \cdot (\sum_{c} \omega_{c,t}^{f,Foreign} \cdot \tau_{c,t}), \tag{3}$$

where $\tau_{f,t}$ is the corporate tax rate faced by firm f in year t, $\omega_{US,t}^{f}$ is the share of firm f's domestic sales[15], $\tau_{fed,t}$ is the U.S. federal tax rate in year t, $\tau_{s,t}$ 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. We set $\tau_{s,t}$ to 0 for states with a gross receipts tax.

Finally, we use $\tau_{f,t}$ to compute the value of the tax shield, i.e. the amount of taxes that firms

[14]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.

[15]Formally using the same notations as above, $\omega_{US,t}^{f} = \frac{\sum_{s\in US} Sales_{s,t}^{f,US}}{\sum_{s\in US} Sales_{s,t}^{f,US} + \sum_{c\notin US} Sales_{c,t}^{f,Foreign}}$.

can save by deducting interest payments to debtholders. Using the formula above, we have:

$$Tax\ Shield_{f,t} = Interest\ Payments_{f,t} \cdot \tau_{f,t}. \tag{4}$$

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 The Tax Cuts and Jobs Act, we set interest payments equal to 30 percent of EBITDA when higher.

3.2 Descriptive Statistics

Table 2 shows summary statistics for our sample, which consists of 13,775 Compustat firm-year observations between 2004 and 2019 for which we observe both carbon emissions and financial information. We measure carbon intensity as the ratio of firms' carbon emissions over sales. 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.

Consider now the corporate taxes faced by U.S. publicly listed corporations. Firms in our sample paid on average 2.2% of their sales in taxes over the period 2004-2019. When we compute the statutory tax rate faced by firms in our sample using the formula (3), we find an average of around 34%. When we compute the tax shield of debt financing using the formula (4), 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.

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.[16] 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]

[16]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.

3.3 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:[17]

$$Taxes/Sales_{i,t} = \beta \times Carbon/Sales_{i,t} + \gamma_t + \gamma_{s,t} + \epsilon_{i,t}, \tag{5}$$

where $Taxes/Sales_{i,t}$ is the firm-level ratio of taxes over sales, $Carbon/Sales_{i,t}$ is the ratio of carbon emissions over sales of firm i in year t, and γ_t are year fixed effects.[18] We further include basic controls for firm size, firm age, the share of foreign sales, and more importantly firm profitability in augmented specifications, in order to estimate the correlation between carbon emissions and taxes paid for firms with the same level of profits. Finally, we also include headquarter state-year fixed effects $\gamma_{s,t}$ in some specifications, 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] We cluster 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 (5) 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. Take 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 (5). We would then conclude that firm A in the emission-intensive

[17] In equation 5, 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, note that we will study the implications of changes in corporate taxation policies on aggregate carbon emissions through a general-equilibrium model in Section 4.

[18] In robustness tests presented in the Online Appendix, 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. We find similar, if anything larger, magnitudes for the estimates.

[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.

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]

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 controls for firm size, age, the share of foreign sales and profitability. 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 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. Note also that the point estimate is similar when we add controls for firm size, age, the share of foreign sales, and more importantly for firm profitability, which is unsurprisingly a significant determinant for profit taxes. Overall, our results indicate that the negative relationship we uncover in Table 3 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]

We assess the robustness of our baseline estimates by considering specifications in which the independent variable is the logarithm of firms' carbon intensity. Panel A of Figure 1 presents a visual representation of the negative relationship between taxes (over sales) and the logarithm of carbon intensity. We report estimates 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, but slightly larger than the one implied by the estimates in Table 3.[23]

[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]An estimate of -1.6 on Log(Carbon/Sales) in Online Appendix Table A.1 indicates that an increase in carbon

[INSERT FIGURE 1]

Before turning to the mechanism behind this tax subsidy, let us emphasize that we do *not* interpret the estimated coefficient $\hat{\beta}$ in equation (5) 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 (5) 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.

3.4 The Mechanism

In this section, we shed 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 in Section 3.4.1, where we show that the tax shield is indeed a key driver of the differences in taxes paid by firms with different carbon intensity. In Section 3.4.4, we take one step further and relate the differential gain from the tax shield to differences in debt levels—and ultimately in asset tangibility—across clean versus dirty firms.

3.4.1 Tax Shield

To explore the mechanism which leads dirty firms to pay lower taxes, we study both the tax shield generated by debt financing and the hypothetical taxes that firms would pay in the absence of the tax shield. We measure the tax shield as in equation (4), i.e. as interest expenses times $\tau_{f,t}$, the corporate tax rate faced by firm f in year t.

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.

As the U.S. tax code allows firms to deduct interest payments from their earnings, one can rewrite the total corporate taxes paid by a given levered U.S. firm as the difference between the hypothetical taxes that the firm would have paid were it entirely equity-financed (which are given by current taxes plus interest expenses $\times$ $\tau_{f,t}$) minus the value of the tax shield (i.e. interest expenses $\times$ $\tau_{f,t}$). According to this decomposition, differences in taxes paid by clean versus dirty firms can come either from differences in firms' profitability, or from differences in the structure of their liabilities.[24] To establish which of the two components drives the correlation with carbon emissions, we estimate our baseline equation (5) separately for each component and present the results in Table 4.

[INSERT TABLE 4]

Columns (1) to (3) of Table 4 show 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 $\times$ 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 Table 3. This indicates that the negative relationship between taxes and emissions presented in Table 3 is explained by a higher tax shield of debt for dirty firms.

To further clarify the role played by the tax shield for the negative relationship between taxes and emissions in Table 3, in Columns (4) to (6) of Table 4 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 at conventional levels, which indicates that there is no robust residual relationship between taxes and carbon emissions, beyond the robust relationship that we uncovered in Columns (1) to (3). To sum up, the relationship between taxes and emissions appears to be largely explained by the fact that dirty firms enjoy a higher tax shield of debt. Panel B of Figure 1 provides a graphical illustration of the relationship between the tax shield and (the logarithm of) firms' carbon intensity.

[24] As noted before, it might also be that dirty firms are more likely to locate their activities in states with lower tax rates. However, we fail to find any robust correlation between carbon intensity and the weighted average state corporate tax rates at the firm level using data from Infogroup and Factset on firms' business activity across U.S. states and across countries.

3.4.2 Robustness

In this subsection, we conduct a series of empirical checks to test the robustness of our baseline findings. Specifically, we present below leave-one-out-industry and yearly estimates, a replication of our results using private firms, sub-sample specifications restricted to domestic versus multinational firms, self-reported versus estimated emissions, carbon emissions from stationary sources reported to the Environmental Protection Agency (EPA), and specifications in which we consider larger sets of firms' emissions, including in turn scope 2 and scope 3 emissions, as well as estimates of firms' marginal instead of statutory tax rates when computing tax shields.

Leave-one-out industry and yearly estimates. We conduct robustness tests to assess whether the relationship between carbon emissions and corporate taxes is driven by a specific time period or a specific sector. 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 statisticall significant in all but one year over the sample period. The estimates for the tax shield are all positive and highly statistically significant. These results are, once again, consistent with the idea that dirty firms benefit from a larger tax shield from debt financing and, thus, pay lower taxes. 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 a leave-one-out specification where we exclude firms in each Bureau of Economic Analysis (BEA) sector. Our results are again robust: the coefficient on carbon emissions remains virtually the same in all leave-one-out specifications, indicating that the implicit subsidy to dirty firms is not driven by a specific sector.

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. For this, we can exploit the fact that Trucost also provides information on carbon emissions for a set of privately-held firms. We then 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 2,633 observations over the same sample period. As shown in column 1 of Panel A and B of robustness Table A.2, the coefficient on carbon emissions is very similar to the one we obtained in our sample of publicly listed firms. Even though we cannot directly test it, 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 might be concerned 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 robustness Table A.2, 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 robustness Table A.2, 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 robustness Table A.2, 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 robustness Table A.2, 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.[25]

Marginal tax rates. Finally, we use estimates of firms' marginal tax rates —developed by Blouin, Core, and Guay (1998)— instead of statutory tax rates to compute the tax shield and find similar results, as shown in column 9 of Panel B of Table A.2. Taken together, these specifications indicate that there is a robust negative relationship between firms' carbon emissions and the taxes they pay on their profits, and that this relationship is driven by the tax shield of debt.

3.4.3 Decomposition of the Tax Shield.

The findings in Table 4 demonstrate that the tax shield of debt explains the negative relationship between taxes and carbon intensity. From its definition in (4), the higher tax shield enjoyed by carbon-intensive firms could be driven by differences in leverage, cost of debt, or tax rates. In 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 equation (3)).

[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 (2), there is a robust 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 ($220 \times 0.068 \times 0.34$) of lower taxes per tonne of

[25] 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.

carbon—a subsidy of the same magnitude than the estimates presented in Tables 3 and 4. Panel A of Figure 2 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, an issue we explore in the next section.

[INSERT FIGURE 2]

3.4.4 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 Figure 2, there is a robust 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 Table 6, which is robust to the introduction of state $\times$ year fixed effects, and controls for firm size, age, share of foreign sales, and profitability. 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 (2) and (3) of, respectively, Table 5 and Table 4, 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 (3) versus (2) of Table 6) and in the one with the tax shield as a dependent variable (Column (5) versus (4) of Table 6). 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 Appendix Table A.4, with and without controlling for firm size, firm age, profitability, and the fraction of foreign sales. 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 Table 6). 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]

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 infeasible given the complexity of corporate taxation), we discuss below two other relevant and quantitatively important features of the taxation of U.S. corporations (and of corporations in other countries) which lead to differential tax burden 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

[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.

[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.

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 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 A.4), we do not expect property taxes to affect disproportionately more carbon-intensive firms.[30]

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 6 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 Appendix Table A.3, we augment the specifications presented in Table 6 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 the fiscal year (in addition to the control variables used in the rest of our paper, namely firm size, firm age, profitability, and the fraction of foreign sales). As shown in column (2) of Appendix Table A.3, adding these variables raises significantly the explanatory power of the econometric model (the R-squared 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

[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)$\times$ 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 firm size, firm age, profitability, and the fraction of foreign sales.

[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.

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-intensitve 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.

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.[31] 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*.[32] 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*.

Table A.5 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

[31] We obtain similar results when we compute implied industry carbon intensity at the SIC2-level instead.

[32] 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.

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.[33] Panel A of Table A.6 shows that dirtier energy producers (as captured by their carbon intensity) rely more on tangible assets, have 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 capaicty (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.

3.5 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 (last available year) 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.[34] This amount is of similar magnitude to the USD 33 billion of carbon pricing revenues raised by governments worldwide in 2017 (World Bank,

[33] We cluster standard errors at the firm level in these specifications to avoid issues arising from too few clusters raised by Moulton (1990).

[34] 5 USD lower taxes, or higher tax shield, per tonne of carbon implied by our estimates in Tables 3 and 4 times 6 giga tonnes of carbon equivalent emitted by the U.S. corporate sector in 2018.

2018).[35] 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 different sectors, indexed by $i \in \mathcal{N}$. 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.

Household.

The representative household purchases goods from firm f at price $p_{f,t}$, and pays consumption tax τ_c. We let $i = \mathcal{I}(f)$ be the sector of firm f. The household supplies labor for a wage w_t, which is taxed at rate τ_h. The household can save through risk-free government bonds $B_{g,t+1}$, risky corporate bonds $B_{f,t+1}$, and equity shares $s_{f,t+1}$. Risk-free bonds pay interest rate r_t. Corporate bonds pay interest rate $r^b_{f,t}$, unless the issuing firm is liquidated. Finally, equity trades at price $Q_{f,t}$ and entitles the owner to dividends $d_{f,t}$, unless default occurs. We describe liquidation and default below, for now we let $\mathcal{L}_{f,t}$ and $\mathcal{D}_{f,t}$ denote the indicator functions of, respectively, the events of liquidation and default for firm f 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.

[35] 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).

The household maximizes

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

subject to the budget constraint

$$\begin{aligned}(1+\tau_c)\sum_{i\in\mathcal{N}}\int_{\mathcal{I}(f)=i}p_{f,t}c_{f,t}df &= (1-\tau_h)w_tL_t+T_t+(1+(1-\tau_h)r_{t-1})B_{g,t}-B_{g,t+1}\\ &+\sum_{i\in\mathcal{N}}\int_{\mathcal{I}(f)=i}\left\{[1+(1-\tau_h)((1-\mathcal{L}_{f,t})r^{b}_{i,t}-\mathcal{L}_{f,t})]B_{f,t}-B_{f,t+1}\right\}df\\ &+\sum_{i\in\mathcal{N}}\int_{\mathcal{I}(f)=i}\left\{[(1-\mathcal{D}_{f,t})(1-\tau_d)(d_{f,t}+Q_{f,t})+\tau_dQ_{f,t-1}]s_{f,t}-Q_{f,t}s_{f,t+1}\right\}df,\end{aligned}$$

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:

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

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

Firms.

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 identifier with the sector identifier. 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.

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

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

$$y_{i,t} = \mathcal{F}_i\left(z_i, \{x_{i,j,t}\}_j, \ell_{i,t}, \{k^s_{i,t}\}_s\right), \tag{6}$$

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 $\bar{\delta}^s_i \in (0,1]$. Firms can vary the amount of capital through investment, by combining inputs from different sectors. We allow the such combinations of inputs to be sector specific. Formally, capital of type s in sector i follows the law of motion:

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

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

Default. Each firm is subject to an idiosyncratic default shock. We assume a tractable process for default, which nonetheless delivers a rich set of implications for interest rates, equity returns and leverage. More specifically, this process will ensure that, in equilibrium both the interest rate on corporate debt and leverage will be sector specific and a function of the amount of tangible capital. The relationship between leverage and asset tangibility is consistent with the empirical evidence. At the same time, the assumption that default and liquidation shocks are exogenous implies that the probabilities of restructuring and liquidation are independent of firm's quantity of debt—a property that will simplify firms' leverage decision substantially.

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, firms' 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. Liquidated firms 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 restructured firms and newly-born ones can purchase the assets that were transferred to households.

Leverage. The default process we have assumed implies that firms can only issue risky corporate 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 in addition to the risky debt just described will not be repaid if the firm defaults. 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

$$b_{i,t+1} \leq \frac{1}{1 + r^b_{i,t+1}} \sum_{s \in \mathcal{S}} \psi_{i,s} q^s_{i,t+1} k^s_{i,t+1}. \tag{7}$$

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. As discussed above, our default process implies that the probabilities of restructuring and liquidation are independent of the quantity of debt. When combined with the assumptions on model parameters we make below—which ensure that equity is more expensive than debt, consistent with empirical evidence—this property simplifies firms' leverage decision as it implies that it is always optimal to issue as much as debt as possible.

Formally, condition (7) 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 6.

Remark. The assumed process for default implies that a firm's leverage increases in its share of tangible assets can borrow more. Corporate rates, however, are independent of such share. It is nonetheless straightforward to extend the default process to make both the amount of borrowing and the cost of debt a function of the share of tangible capital: all is needed is to assume that lenders recover a fraction of tangible capital even if the firm is liquidated.

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; we consider such expenses as investment in intangible capital. Finally, firms must pay a property tax on existing capital. Formally, taxable income and dividends equal, respectively,

$$TI_{i,t} = p_{i,t}y_{i,t} - \sum_{j\in\mathcal{N}} p_{j,t}x_{i,j,t} - w_t\ell_{i,t} - \sum_{s\in\mathcal{T}} \bar{\delta}_i^s q_{i,t}^s k_{i,t}^s - \sum_{s\in\mathcal{I}} q_{i,t}^s I_{i,t}^s - \sum_{s\in\mathcal{S}} \tau_k^s q_{i,t}^s k_{i,t}^s - r_{i,t}^b b_{i,t}$$

and

$$d_{i,t} = (1-\tau_p)TI_{i,t} - \sum_{s\in\mathcal{T}} q_{i,t}^s (k_{i,t+1}^s - k_{i,t}^s) + b_{i,t+1} - b_{i,t},$$

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

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 $E_t = \sum_i E_{i,t}$.

Remark. Let us emphasize that the emission rate is assumed to be invariant to policy. It follows that policy changes affect emissions only insofar as they affect production. A more general assumption would be to allow firms to react to policy by investing in cleaner technologies. Although we find such a channel to be extremely relevant, we do not pursue it here.

Government, Market Clearing and Equilibrium

We conclude the description of the model with government policies and market-clearing conditions. 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

$$TR_t + B_{g,t+1} = (1 + r_{t-1})B_{g,t} + T_t, \tag{8}$$

where tax revenues TR_t are given by

$$TR_t \equiv \tau_c \sum_{i\in\mathcal{N}} p_{i,t}c_{i,t} + \tau_h w_t L_t + \tau_h r_{t-1}B_{g,t} + \sum_{i\in\mathcal{N}} \Big\{TI_{i,t} + TP_{i,t} + \sum_{s\in\mathcal{S}} \tau_k^s q_{i,t}^s k_{i,t}^s\Big\},$$

where $TI_{i,t}$ and $TP_{i,t}$ are, respectively, tax revenues from portfolio investment and profits in sector i,[36] 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 $(\rho_i + \lambda_i)$ in sector i is in default.

Equilibrium. 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:

$$y_{i,t} = c_{i,t} + \sum_{j\in\mathcal{N}} x_{j,i,t} + \sum_{s\in\mathcal{S},j\in\mathcal{N}} i_{j,i,t}^s \quad \text{and} \quad L_t = \sum_{i\in\mathcal{N}} \ell_{i,t}; \tag{9}$$

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

[36] In particular, tax revenues from portfolio investments equal $TI_{i,t} = \tau_h(1-\lambda_i)r_{i,t}^b b_{i,t} + \tau_d[(1-\rho_i-\lambda_i)(d_{i,t}+Q_{i,t}) - Q_{i,t-1}]$, and tax revenues profits equal $TP_{i,t} \equiv \tau_p[p_{i,t}y_{i,t} - \sum_{j\in\mathcal{N}} p_{j,t}x_{i,j,t} - w_t\ell_{i,t} - \sum_{s\in\mathcal{I}} q_{i,t}^s I_{i,t}^s - \sum_{s\in\mathcal{T}} \bar{\delta}_i^s q_{i,t}^s k_{i,t}^s - \sum_{s\in\mathcal{S}} \tau_k^s q_{i,t}^s k_{i,t}^s - r_{i,t}^b b_{i,t}]$.

4.1 Preliminary Results

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

$$p_{i,t}c_{i,t} = \theta_i P_t C_t, \tag{10}$$

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

$$\frac{V'(L_t)}{U'(C_t)} = \frac{1-\tau_h}{1+\tau_c} w_t. \tag{11}$$

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:

$$r^b_{i,t+1} = \frac{\lambda_i + (1-\tau_h)r_t}{(1-\tau_h)(1-\lambda_i)} \tag{12}$$

and

$$r^e_{i,t+1} \equiv \frac{d_{i,t+1} + Q_{i,t+1}}{Q_{i,t}} - 1 = \frac{(1-\tau_d)(\rho_i + \lambda_i) + (1-\tau_h)r_t}{(1-\tau_d)(1-\rho_i-\lambda_i)}. \tag{13}$$

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.

For convenience, we let $\xi^D_{i,t+1}$ and $\xi^E_{i,t+1}$ be the extra compensation, over and above the risk-free rate, that corporate bonds and equity must pay due to default risk and taxes, that is, $\xi^D_{i,t+1} \equiv r^b_{i,t+1} - r_t$ and $\xi^E_{i,t+1} \equiv r^e_{i,t+1} - r_t$. In what follows, we assume that $\xi^E_{i,t+1} \geq \xi^D_{i,t+1}$ for all industries. This assumption, which is satisfied by virtually all industries in our calibration, requires ρ_i, i.e. the probability of restructuring, is sufficiently high relative to λ_i, i.e. the probability of liquidation. In fact, in the absence of taxes, it would be equivalent to $\rho_i \geq \lambda_i$.

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:

$$\mathcal{F}_i\left(z_i, \{x_{i,j,t}\}_j, \ell_{i,t}, \{k^s_{i,t}\}_s\right) = z_i \zeta_i \Big(\prod_{j\in\mathcal{N}} x_{i,j,t}^{\alpha_{ij}}\Big)^{1-\gamma_i} \Big(\ell_{i,t}^{\phi_i^\ell} \prod_{s\in\mathcal{S}} \left(k^s_{i,t}\right)^{\phi_i^s}\Big)^{\gamma_i}, \tag{14}$$

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

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

$$\mu_i \phi_i^\ell \gamma_i = \frac{w_t \ell_{i,t}}{p_{i,t} y_{i,t}} \tag{15}$$

and

$$\mu_i \alpha_{ij}(1-\gamma_i) = \frac{p_{j,t} x_{i,j,t}}{p_{i,t} y_{i,t}}, \tag{16}$$

respectively, where $\mu_i \equiv (\sigma_i - 1)/\sigma_i$ is the inverse of the mark-up. Also, conditional on total investment $I^s_{i,t}$, the optimal choice of $i^s_{i,j,t}$ is also static and satisfies

$$i^s_{i,j,t} = \frac{1}{p_{j,t}} \omega^s_{ij} q^s_{i,t} I^s_{i,t}, \tag{17}$$

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

The only dynamic choice is the one about investment $I^s_{i,t}$. The optimal choice of tangible capital,

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

[38] $\zeta_i \equiv (\gamma_i \phi_i^\ell)^{-\gamma_i \phi_i^\ell} \prod_j ((1-\gamma_i)\alpha_{ij})^{-(1-\gamma_i)\alpha_{ij}} \prod_s (\gamma_i \phi_i^s)^{-\gamma_i \phi_i^s}$.

i.e., type-s capital with $s \in \mathcal{T}$, satisfies:

$$\mu_i \phi_i^s \gamma_i = R_{i,t}^s \frac{q_{i,t}^s k_{i,t}^s}{p_{i,t} y_{i,t}}, \tag{18}$$

where the rental rate $R_{i,t}^s$ of type-s capital is defined as (the expression for intangible capital is analogous).

$$R_{i,t}^s \equiv \bar{\delta}_i^s + \tau_k^s + r_{i,t}^b \frac{\psi_{i,s}}{1 + r_{i,t}^b} + \frac{1}{1-\tau_p} r_{i,t}^e \left(1 - \frac{\psi_{i,s}}{1 + r_{i,t}^b}\right) + \frac{1}{1-\tau_p}(1 + r_{i,t}^e)\left(\frac{q_{i,t-1}^s}{q_{i,t}^s} - 1\right). \tag{19}$$

The rental rate represents the user cost of capital to the firm. It is the sum of depreciation, the tax on capital, and the financing cost that the firm must incur to purchase capital, coming from both debt and equity. The last term captures the fact that the cost of using capital increases if the price of capital decreases over time, it becomes more costly for the firm to use capital. Finally, notice that the factor $1/(1-\tau_p)$ multiplies only the equity terms (i.e., the last two terms). This is because debt enjoys a tax shield. It follows that, all other things equal, the rental rate falls if firms can finance a higher fraction of capital with debt.

4.2 Calibration

We focus on the corporate sector, excluding the government and housing. We consider exports as final consumption and assume that all output is produced domestically. We study counterfactuals using "exact hat algebra" (Dekle, Eaton, and Kortum, 2008; Costinot and Rodríguez-Clare, 2014), that is, we express equilibrium relations in terms of changes from the baseline equilibrium. Thus, for example, letting $X_{i,t}'$ and $X_{i,t}$ denote an endogenous variable before and after the policy change, respectively, we express 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 $\sigma = 1.7$ 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 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 will correspond to the value added share of sector i, while ϕ_i^ℓ, ϕ_i^s and α_{ij} with, 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 Lehn and Winberry (2020).[39] 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 aggregate these assets into three types of capital: equipment, non-residential structures, and intangible assets.

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 $\psi_{i,s} = \bar{\psi}_i + \hat{\psi}$ for tangible capital, and $\psi_{i,s} = \bar{\psi}_i$ for intangible capital. We then use condition (7), which must hold 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 $\hat{\psi} = 0.43$. We finally set $\bar{\psi}_i$ equal to the regression residuals.

To compute rental rates, we use formula (19). In particular, for each of the 31 types of assets, we use data on depreciation rates, prices of capital, tax rates, interest rates and leverage and compute the rental rate as a function of sector i's return on equity $r^e_{i,t+1}$. We then estimate the latter using the fact that value added must equal total payments to labor, capital and profits. This estimation

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

strategy is the one proposed in Karabarbounis and Neiman (2019). We extend their analysis along two dimensions. First, while the focus of that paper is on aggregate variables, we allow rental rates to vary with the type of capital and with the firm's sector; in addition, we estimate sector-specific equity returns. Second, our formula separately accounts for interest expenses—which are shielded from the profit tax—and equity payouts—which are subject to the profit tax.

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).

4.3 A Counterfactual 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 expenses on corporate debt, and compare its steady state to the one of the original economy in which debt enjoys a tax shield. We compute the relative change of several variables of interest, both at the aggregate and at the sector level. Our main analysis uses the full model, which includes the rich input-output network for intermediates and capital inputs. We later discuss the role of input-output linkages in amplifying or dampening the impact of policy on aggregate emissions.

Overall, following the removal of the tax shield, aggregate output in steady state falls by 3.01%, while aggregate consumption decreases by 2.39%. This change is brought about mostly by a reduction in steady-state capital; the variation in aggregate labor is, instead, very small (0.35%). The fall in output is accompanied by a much larger reduction in total emissions (−6.08%), which suggests that the reduction in output is not uniform across sectors.

[INSERT FIGURE 3]

Figure 3 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 (i.e., structures and equipment); 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. Intuitively, since emissions in every sector are proportional to the sector's output, the total change in emissions is a function of the *correlation* between changes in production and carbon intensity across sectors. Intuitively, if cuts in production are concentrated in the more polluting sectors, then total emissions will fall by more. The model generates this covariance quite naturally through two ingredients—both of which are motivated by the empirical evidence of 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. It is instructive to work through the details of this argument.

A closer look at the mechanism. Let's start with the impact of the no-tax-shield policy on the rental rate of capital (19). In steady state, the expression reduces to (we drop the time subscript to denote steady-state variables)

$$R_i^s = \bar{\delta}_i^s + \tau_k^s + r_i^b \frac{\psi_{i,s}}{1+r_i^b} + \frac{1}{1-\tau_p} r_i^e \Big(1 - \frac{\psi_{i,s}}{1+r_i^b}\Big), \tag{20}$$

for $s \in \mathcal{T}$. When the tax shield is removed, the term capturing the cost of debt (the third term) gets multiplied by the factor $1/(1-\tau_p)$, exactly as the term capturing the cost of equity (the last term). As a result, the rental rate increases by $\Delta R_i^s = \tau_p/(1-\tau_p) r_i^b \psi_{i,s}/(1+r_i^b)$. Notice that the change is proportional to $\psi_{i,s}$, i.e., the collateral value of type-s capital. Thus, 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.

Following the change in the rental rate, firms respond by raising their prices. As a result, production decreases and so do emissions, which are proportional to output. It turns out that, up to a first-order approximation, we can derive a sharp characterization for the partial-equilibrium response of the model. In fact, such a characterization does not even require the Cobb-Douglas assumption: it suffices that the production function exhibits constant returns to scale. Focusing on a single firm's problem and keeping all other prices (e.g., investment price, wages, etc.) constant, we can express the percentage change in the firm's emissions as follows:

$$d \log E_f = \frac{d \log \mathcal{D}_f}{d \log p_f} \times \sum_{s \in \mathcal{S}} \frac{d \log \mathcal{MC}_f}{dR_i^s} \times \Delta R_i^s. \tag{21}$$

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

To sum up, following a policy that removes the tax shield, firms holding more capital—and, in particular, more *tangible* capital—experience a larger increase in their production costs. All other things equal, they respond by charging a higher price, thus, cutting production and emissions by more. Finally, notice that equation (21) provides a theoretical motivation for our empirical analysis. In particular, the model predicts that emissions should be a function of assets (PPE in our empirical analysis) scaled by firms' sales.

4.4 Carbon Tax: An Equivalent Representation

In this section we introduce a carbon tax—i.e., a direct tax on a firm's carbon emissions. The purpose for considering such a policy is twofold. First, as the carbon tax is arguably the most widely-known policy to target carbon emissions, it represents a significant benchmark for our tax-shield channel. Second, we can represent our no-tax-shield policy as the sum of a carbon tax plus an "error" term. In light of this representation, we will be able to reinterpret the no-tax-shield policy as a "distorted"—and, hence, less targeted—carbon tax.

To quantify the impact of the no-tax-shield policy, we simulate an economy in which interest expenses are deductible, but firms are subject to a tax on carbon emissions. Formally, we let τ_e be the carbon tax, thus, a firm with emissions $E_{f,t}$ must pay $\tau_e E_{f,t}$. We then set τ_e so that the

Table 1. Comparison between a policy that removes the tax shield of debt and a carbon tax designed to achieve the same fall in aggregate carbon emissions

	No tax shield	Carbon tax (USD 26.72)
Δ emissions	-6.08%	-6.08%
Δ output	-3.01%	-1.36%
Δ consumption	-2.39%	-0.82%

carbon tax produces the same drop in emissions as the counterfactual economy in Section 4.3.[40] The resulting tax rate is USD 26.72.

Table 1 summarizes the impact of the carbon tax on output and consumption. The first column reports the change in emissions, output, and consumption in the counterfactual economy of Section 4.3. The second column contains the analogous quantities for the carbon-tax economy. The carbon tax achieves the same drop in emissions with a lower cost in terms of (steady-state) output and consumption.

We can also derive the analogue of decomposition (21) for the carbon tax. We can then express the percentage change in the firm's emissions following the introduction of carbon tax as follows:

$$d \log E_f = \frac{d \log \mathcal{D}_f}{d \log p_f} \times \frac{d \log \mathcal{MC}_f}{d\tau_e} \times \tau_e. \tag{22}$$

The first term is exactly as in equation (21). The second term captures the change in the firm's marginal cost due to carbon tax. In Appendix B.1, we show that it is proportional to the firm's emissions scaled by sales, i.e., $d \log \mathcal{MC}_f / d\tau_e \propto E_f / p_f y_f$. Not surprisingly, firms with higher emissions will be hurt more from a carbon tax.

By comparing the partial-equilibrium impact on emissions of the two policies given by (21) and (22), one might be tempted to conclude that the two policies are tightly connected. This intuition is correct. In fact, we can derive an equivalent representation of our no-tax-shield policy in terms of an alternative policy involving a carbon tax. More specifically, define the tax shield as

[40] Alternatively, we could set the carbon tax to produce the same drop in output (or consumption) as the no-tax-shield policy. Although these alternative scenarios produce similar results, we find that targeting the drop in emissions is the cleanest counterfactual.

$TS_f \equiv \tau_p r_i^b b_f$, and notice that we can always find a constant β and a variable ϵ_f such that

$$\frac{TS_f}{p_f y_f} = \beta \times \frac{E_f}{p_f y_f} + \epsilon_f, \tag{23}$$

where, in addition, the "error term" ϵ_f is orthogonal to the right-hand-side variable. Equation (23) is thus the OLS regression of tax shield on emissions (both of them scaled by firm's sales).

Equation (23) provides a novel interpretation for the tax shield and, as a result, for the policy that removes it. Since more carbon-intensive firms enjoy a larger tax shield, the calibrated model features a negative coefficient β. It follows that the tax shield is equivalent to a negative carbon tax (a subsidy to emissions!) plus a firm-specific *revenue* tax—i.e., a tax that is proportional to firm's revenues $p_f y_f$ and equal to ϵ_f. This revenue tax—which, by construction, is orthogonal to carbon emissions—is responsible for the less targeted nature of our tax-shield-policy relative to a carbon tax and, ultimately, for the larger drop in output and consumption reported in Table 1. In the appendix, we formalize this argument showing that the two policies—the no-tax-shield policy and the combination of a carbon tax and a revenue tax just described—have identical effects up to a first-order approximation[41]

Let us conclude by remarking that, as it was also the case for the no-tax-shield policy, condition (23) provides a theoretical justification for our empirical analysis. In fact, one can read the analysis in Section 3.4.1—where tax shield (scaled by sales) is regressed on emissions (scaled by sales)—as the empirical counterpart of condition (23).

4.5 A Budget-Neutral Policy

So far we have abstracted from government budget. This is without consequence when, like in our model, the government has access to lump-sum taxes. Things, however, are not so simple when governments need to change other taxes to restore budget balance, and such taxes could in principle affect emissions. Another potential objection is that our no-tax-shield policy causes output and consumption to fall. This is to be expected from a policy that essentially raises taxes on the corporate sector. However, the price in terms of foregone consumption of the reduction in

[41]More precisely, the general-equilibrium effect of the two policies is identical up to a first-order approximation.

emissions might be too dear: is the proposed policy worth it in terms of overall welfare?

In this section, we provide a simple way to address these concerns. 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 by not 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, 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.

[INSERT FIGURE 4]

Figure 4 illustrates the counterfactual economy with the two aforementioned policies. The understand the figure, consider first the point on the horizontal axis corresponding to 0. This is exactly the case studied in Section 4.3, where only the tax shield is removed. Corresponding to the zero point, therefore, we find the changes in output and emissions reported in Table 1. 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 point is the one in which the government-budget line crosses zero, and the policy is budget-neutral. The second point is the one in which the GDP line crosses zero. Under this policy the economy produces the same GDP as in the status quo. Importantly, the change in emissions is negative in both of these cases. The figure suggests, for example, that a properly designed policy can achieve a fall in total emissions of about 2% without any noticeable change in GDP. Such a policy reform would most likely increase welfare.

5 Conclusion

This paper studies the role of corporate profit taxation for carbon emissions. We document that, counter to optimal taxation in the presence of pollution externalities, dirty firms pay lower profit taxes. This carbon bias of profit taxation stems from the fiscal advantage of corporate debt, since dirty firms use more tangible capital, which allows them to borrow more. Finally, we build a general-equilibrium framework in which carbon emissions are a byproduct of firm activity and study the aggregate implications of different corporate taxation schemes. The model suggests that a simple policy that removes the tax shield of debt can substantially reduce carbon emissions in steady state.

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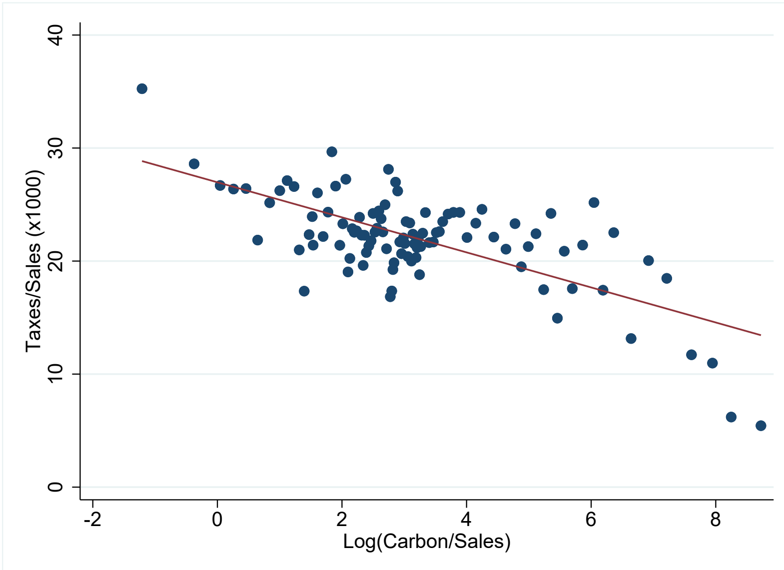
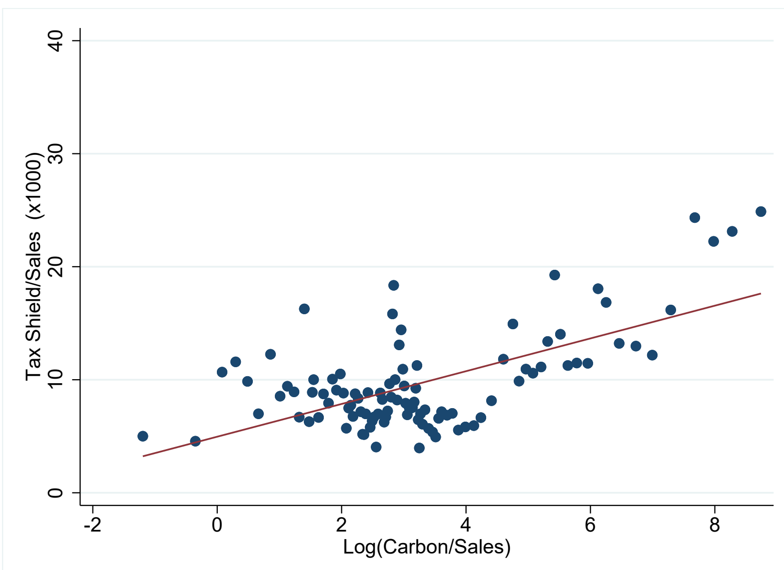
Figures and Tables

Figure 1. The tax advantage of carbon-intensive firms

Panel A. Profit Taxes (TXPD over Sales)



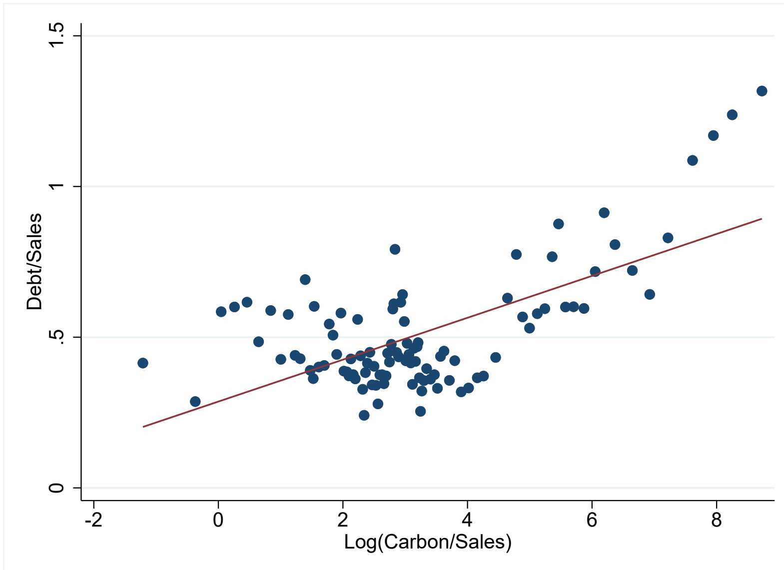
Panel B. Tax Shield (Interest×Tax Rate/Sales)



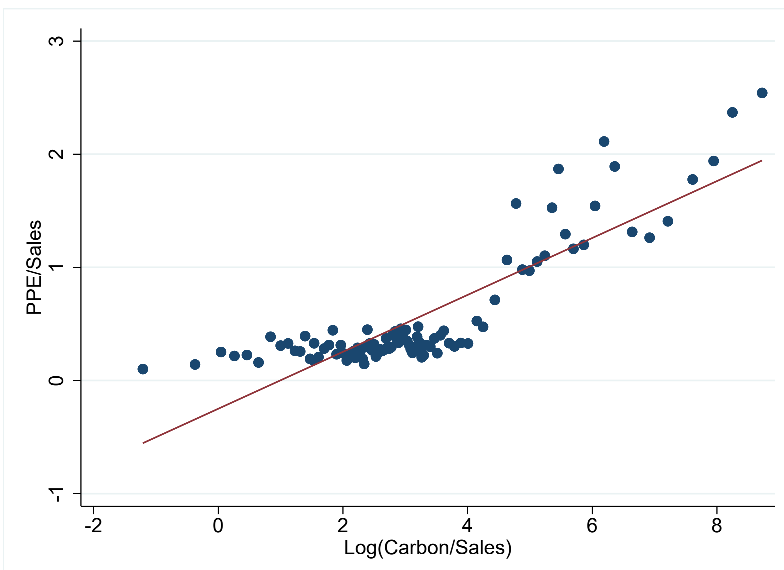
Note: This scatter plot reports the relationship between the logarithm of firms' carbon emissions over total sales and respectively corporate taxes over sales (Panel A), and tax shield over sales (Panel B) over the sample period 2004-2019, after absorbing year fixed effects. Each dot represents an equal size bin of firms' carbon emissions over total sales (100 bins). Tax shield is computed as interest payments times the firm-level statutory tax rate scaled by firm sales. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. Data on carbon emissions are from Trucost. Financial data are from Compustat. Information on firms' employees and sales across states are retrieved from Infogroup, on sales by country from Factset, and on tax rates from Tax Foundation.

Figure 2. Carbon-intensity, leverage, and asset tangibility

Panel A. Leverage

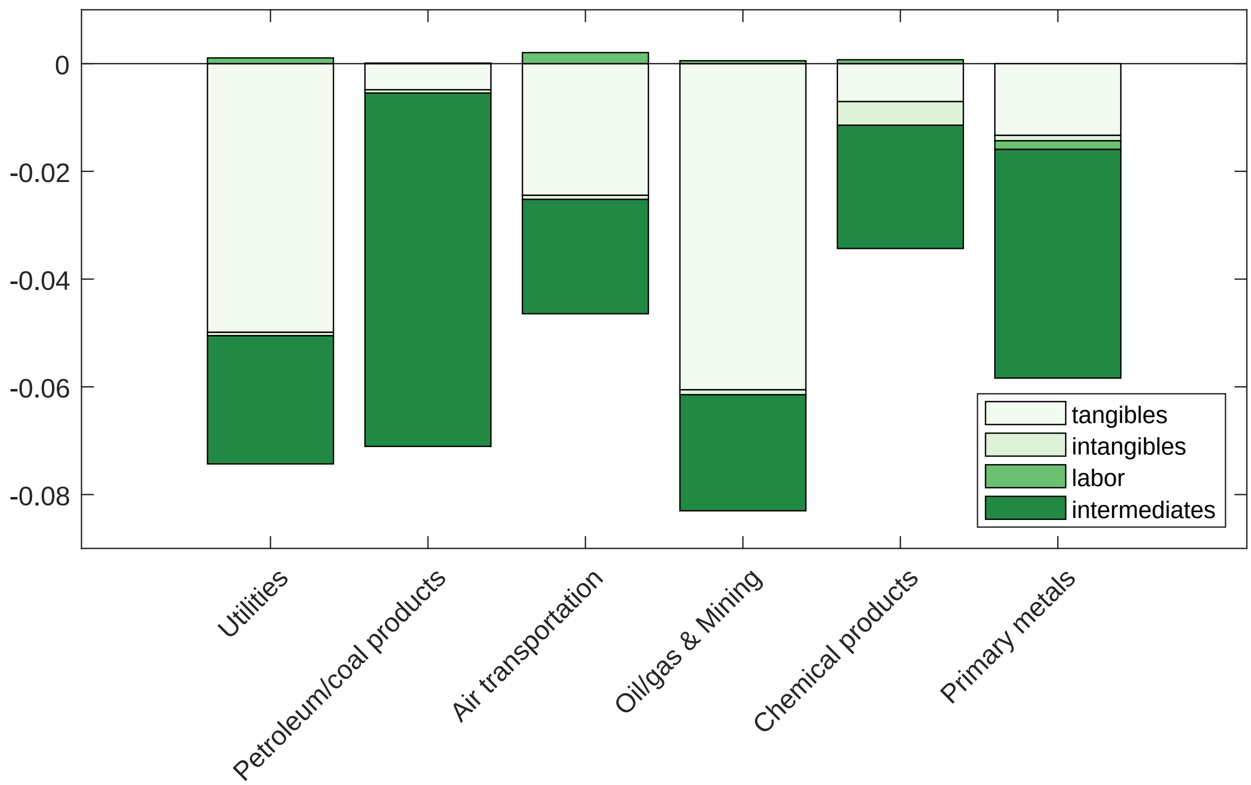


Panel B. Asset Tangibility



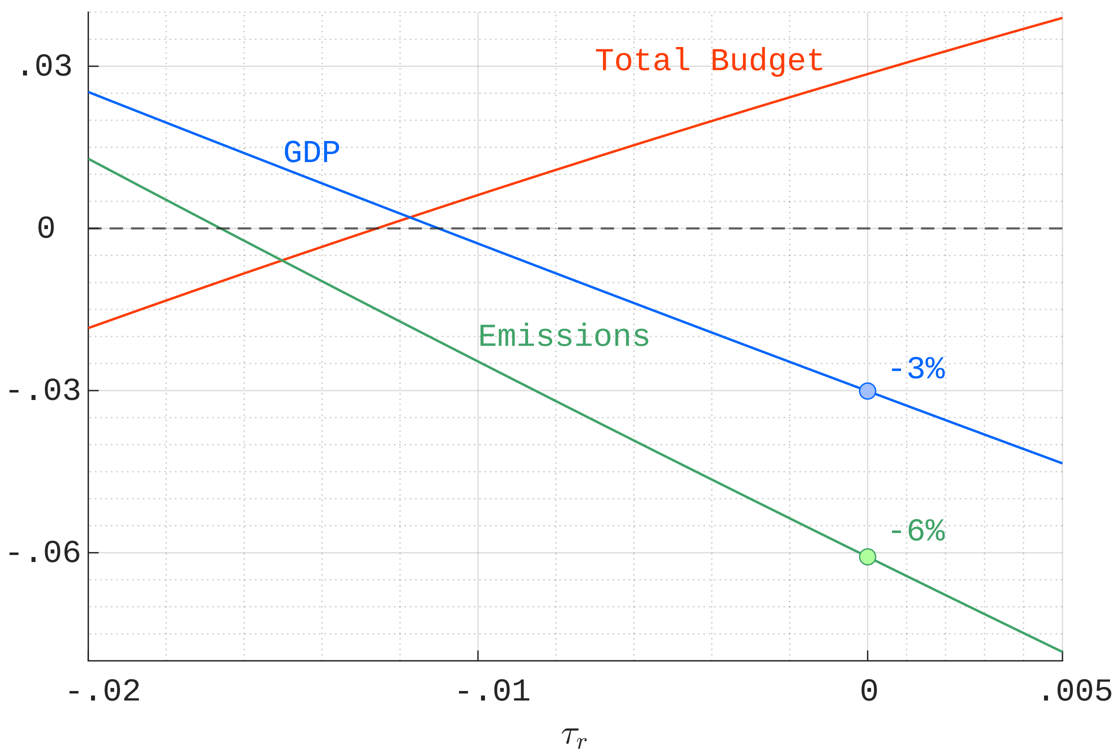
Note: This scatter plot reports the relationship between the logarithm of firms' carbon emissions over total sales and either debt over sales (in Panel A) or property, plant, and equipment over sales (in Panel B) over the sample period 2004-2019, after absorbing year fixed effects. Each dot represents 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 3. Counterfactual economy without the tax shield



Note: Response of output and different inputs to a policy that removes the tax shield of debt, for the six most carbon-intensive sectors.

Figure 4. Budget-neutral policy



Note: 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

	(1)	(2)	(3)	(4)	(5)	(6)
	Obs.	Mean	SD	p1	p50	p99
Carbon Emissions						
Carbon/Sales (tonnes of CO_2 per k. Sales)	13,775	0.220	0.712	0.000	0.019	4.627
Taxes paid by U.S. corporations						
Tax/Sales	13,775	0.022	0.026	-0.020	0.015	0.126
Tax Shield/Sales	13,775	0.010	0.015	0.000	0.005	0.082
(Tax+Tax Shield)/Sales	13,775	0.032	0.030	-0.008	0.025	0.157
Firm (Statutory) Tax Rate (in %)	33.740	5.222	22.971	35.000	40.833	
Other variables						
Sales (in USD Million)	13,775	11030.531	31700.924	23.446	2827.481	145224.805
Firm Age	13,775	45.780	30.219	4.000	39.000	128.000
EBITDA/Sales	13,775	0.117	0.400	-2.736	0.155	0.622
Share Foreign	13,775	0.267	0.274	0.000	0.189	0.944
Debt/Sales	13,775	0.511	0.643	0.000	0.300	3.526
Interest Rate (Interest/Debt, in %)	13,775	6.786	5.043	1.286	5.623	29.564
PPE/Sales	13,775	0.562	0.914	0.010	0.203	4.700

Note: This table presents summary statistics for our sample, which consists of 13,775 firm-year observations between 2004 and 2019. There are 1,917 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. The main variable of interest Carbon/Sales is expressed in tonnes of CO_2 equivalent per thousands of sales. Taxes are Compustat item TXPD, 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 payments are Compustat item XINT. Tax shield is computed as interest payments times the firm-level statutory tax rate. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. Data on carbon emissions are from Trucost. Financial data are from Compustat North America Fundamentals. Information on firms' employees and sales across states are retrieved from Infogroup, on sales by country from Factset, and on state and country-level tax rates from Tax Foundation.

Table 3. Corporate taxes and carbon emissions

	(1)	(2)	(3)	(4)	(5)	(6)
	Corp. Taxes per k. Sales					
Carbon Intensity	-4.135***	-4.452***	-4.359***	-4.149***	-6.376***	-6.372***
(tonnes of CO_2 per k. Sales)	(0.578)	(0.571)	(0.669)	(1.102)	(1.158)	(1.108)
Year FE	Y	Y		Y	Y	
HQ State x Year FE			Y			Y
Firm Controls		Y	Y		Y	Y
Size Weights				Y	Y	Y
r2	0.071	0.135	0.190	0.041	0.336	0.416
N	13,775	13,775	13,775	13,775	13,775	13,775

Note: This table presents estimates from pooled OLS specifications of firms' corporate taxes paid over sales on the ratio of firms' carbon emissions over 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. Specifications are weighted with firms' lagged sales in Columns (4) to (6). 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. Tax shield and carbon emissions

	(1)	(2)	(3)	(4)	(5)	(6)
				Hypothetical Taxes		
	Tax Shield			Assuming 100% Equity		
	Interest×Tax Rate/Sales (× 1,000)			(Tax+Tax Shield)/Sales (× 1,000)		
Carbon Intensity	4.358***	4.499***	4.451***	0.090	0.091	0.132
(tonnes of CO_2 per k. Sales)	(0.565)	(0.638)	(0.524)	(1.007)	(1.036)	(1.029)
Year FE	Y	Y		Y	Y	
HQ State x Year FE			Y			Y
Firm Controls		Y	Y		Y	Y
r2	0.050	0.147	0.207	0.046	0.052	0.104
N	13,775	13,775	13,775	13,775	13,775	13,775

Note: This table presents estimates from pooled OLS specifications of tax shield and hypothetical taxes assuming firms are 100% equity financed (scaled by firms' sales) on 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. Hypothetical taxes assuming firms are 100% equity financed are computed as the sum of corporate taxes paid and tax shield scaled by firms' 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 5. Decomposition of the tax shield advantage of carbon-intensive firms

	(1) Tax Shield ($\times$ 1000)	(2) Debt/Sales	(3) Interest	(4) Tax Rate
Carbon Intensity	4.451***	0.219***	-0.017	-0.007
(tonnes of CO_2 per k. Sales)	(0.524)	(0.022)	(0.091)	(0.037)
HQ State x Year FE	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y
r2	0.207	0.158	0.139	0.856
N	13,775	13,775	13,775	13,775

Note: This table presents estimates from pooled OLS specifications of tax shield over sales in Column (1), debt over sales in Column (2), interest rate on debt in Column (3), and firm-level profit tax rate in Column (4), on 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. 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. 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.

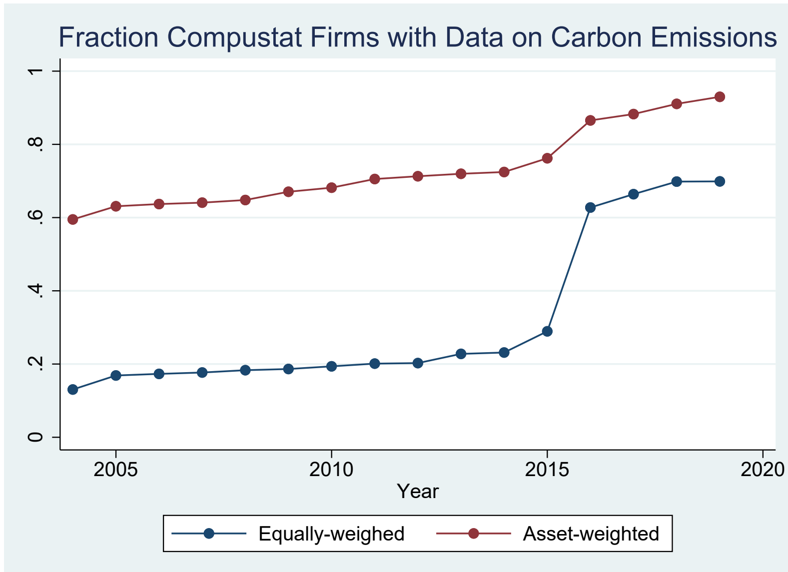
Table 6. Carbon-intensity, debt and asset tangibility

	(1)	(2)	(3)	(4)	(5)
	PPE/Sales	Debt/Sales		Tax Shield ($\times$ 1,000)	
Carbon Intensity	0.512***	0.219***	-0.014	4.451***	0.051
(tonnes of CO_2 per k. Sales)	(0.035)	(0.022)	(0.027)	(0.524)	(0.587)
PPE/Sales			0.455***		8.708***
			(0.041)		(0.694)
HQ State x Year FE	Y	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y	Y
r2	0.325	0.158	0.439	0.207	0.402
N	13,775	13,775	13,775	13,775	13,775

Note: This table presents estimates from cross-sectional specifications of plant, property and equipment over sales in Column (1), debt over sales in Columns (2) to (3), and tax shield in Columns (4) to (5), on 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. 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.

A Appendix: Supplemental Empirical Analyses

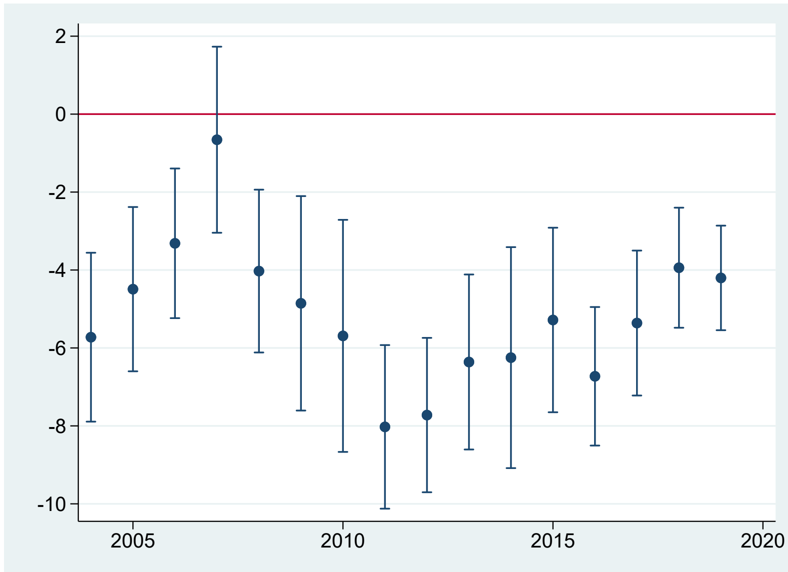
Figure A.1. Coverage of Compustat firms with data on carbon emissions in Trucost



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. Profit Taxes

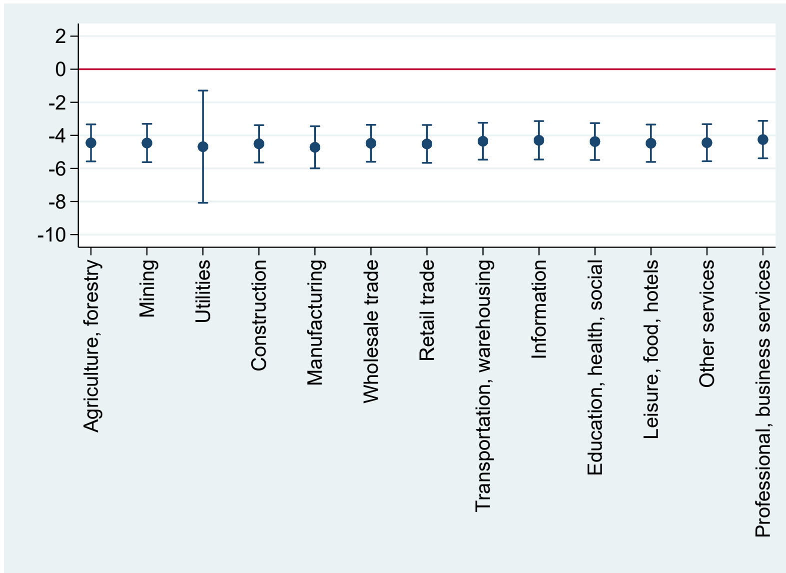


Panel B. Tax Shield

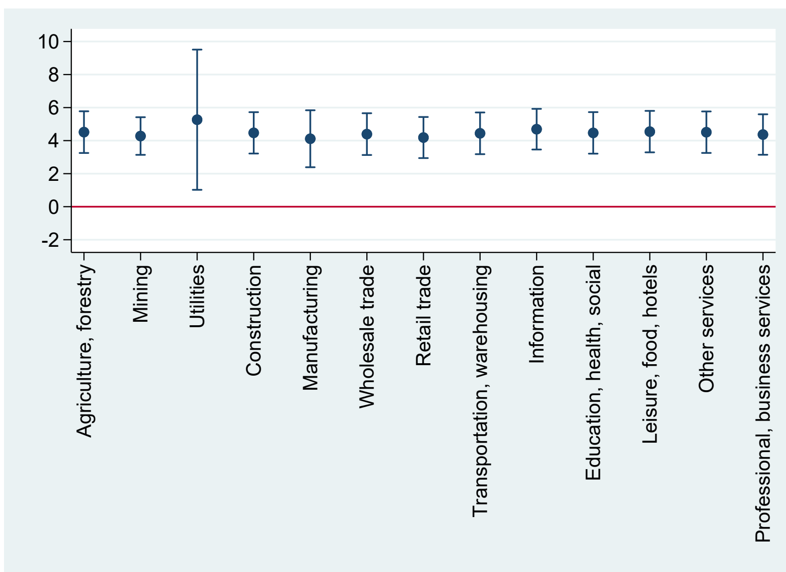
Note: This figure displays yearly estimates of cross-sectional regressions of respectively corporate taxes over sales (Panel A), and tax shield over sales (Panel B) on the ratio of firms' carbon emissions over sales for the sample period 2004-2019, after absorbing (headquarter) state fixed effects and 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. Data on carbon emissions are from Trucost. Financial data are from Compustat North America Fundamentals. Information on firms' employees and sales across states are retrieved from Infogroup, on sales by country from Factset, and on tax rates from Tax Foundation.

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

Panel A. Profit Taxes



Panel B. Tax Shield



Note: This figure displays estimates of pooled OLS regressions of respectively corporate 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. Data on carbon emissions are from Trucost. Financial data are from Compustat. Information on firms' employees and sales across states are retrieved from Infogroup, on sales by country from Factset, and on tax rates from Tax Foundation.

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

	Taxes per k. Sales			Tax Shield per k. Sales		
Log(Carbon Intensity)	-1.563***	-1.740***	-1.591***	1.445***	1.511***	1.402***
	(0.438)	(0.414)	(0.466)	(0.466)	(0.468)	(0.442)
Year FE	Y	Y		Y	Y	
HQ State x Year FE			Y			Y
Firm Controls		Y	Y		Y	Y
r2	0.071	0.136	0.188	0.039	0.136	0.192
N	13,775	13,775	13,775	13,775	13,775	13,775

Note: This table presents estimates from pooled OLS specifications of firms' corporate taxes paid 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. 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. Corporate taxes, tax shield and carbon emissions - Robustness

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A:	Corp. Taxes per k. Sales								
Carbon Intensity	-3.506***	-3.732***	-4.177***	-6.685***	-4.086***	-4.518***	-4.186***	-3.929***	
(tonnes of CO_2 per k. Sales)	(0.844)	(0.712)	(1.520)	(1.315)	(0.875)	(1.114)	(0.676)	(0.639)	
r2	0.277	0.272	0.219	0.359	0.202	0.172	0.189	0.189	
N	2,633	4,073	9,541	2,320	11,137	11,564	13,775	13,775	
Panel B:	Tax shield per k. Sales								
Carbon Intensity	4.638***	4.223***	4.976***	3.650***	4.809***	4.304***	4.336***	3.619***	3.752***
(tonnes of CO_2 per k. Sales)	(0.686)	(0.592)	(0.962)	(0.502)	(0.740)	(0.971)	(0.516)	(0.519)	(0.471)
r2	0.337	0.264	0.156	0.513	0.200	0.216	0.206	0.199	0.199
N	2,633	4,073	9,541	2,320	11,137	11,564	13,775	13,775	12,485
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 firms' corporate taxes paid (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 (1998) 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 A.3. Carbon-intensity, debt and asset tangibility - Controlling for other determinants of leverage

	(1)	(2)	(3)	(4)	(5)	(6)
	Debt/Sales			Tax Shield ($\times$ 1,000)		
Carbon Intensity	0.220***	0.174***	-0.021	4.366***	3.617***	0.028
(tonnes of CO_2 per k. Sales)	(0.021)	(0.022)	(0.025)	(0.448)	(0.516)	(0.571)
PPE/Sales			0.433***			8.075***
			(0.036)			(0.687)
Rated		0.384***	0.232***		7.969***	5.179***
		(0.052)	(0.025)		(1.211)	(0.580)
Dividend Payer		0.020	-0.044**		0.058	-1.209**
		(0.034)	(0.022)		(0.788)	(0.574)
M/B		-0.051***	-0.021*		-0.891**	-0.259
		(0.016)	(0.012)		(0.375)	(0.299)
Cash-Flow Volatility		0.103	0.094**		7.718**	7.505***
		(0.095)	(0.046)		(3.011)	(1.872)
Depreciation/Assets		0.088	-2.199***		38.120**	-4.902
		(0.807)	(0.534)		(18.914)	(12.884)
RD/Sales		0.744**	0.418*		12.758*	5.902
		(0.305)	(0.223)		(6.963)	(5.607)
Advertising/Sales		-0.114	0.714**		-12.093	4.238
		(0.397)	(0.359)		(7.338)	(6.135)
EBITDA/Sales		0.296	0.021		-0.578	-6.365*
		(0.234)	(0.148)		(4.910)	(3.292)
Log(Sales)		-0.067***	-0.012		-1.978***	-0.943***
		(0.016)	(0.009)		(0.353)	(0.208)
Log(Firm Age)		-0.064**	-0.061***		-1.094	-0.961*
		(0.031)	(0.021)		(0.791)	(0.572)
Share Foreign		-0.208***	-0.009		-6.991***	-3.269***
		(0.066)	(0.047)		(1.420)	(1.101)
HQ State x Year FE	Y	Y	Y	Y	Y	Y
r2	0.138	0.256	0.482	0.119	0.286	0.435
N	13,775	13,508	13,508	13,775	12,902	12,902

Note: This table presents the same specifications as in Columns (2) and (4) of Table 6 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.4. 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
r2	0.230	0.196	0.320	0.171	0.205	0.141	0.085
N	8206	8206	8206	8206	8206	8206	8206
Panel B: With Firm Controls	GrossPPE/Sales	Machinery/Sales	Buildings/Sales	Leases/Sales	Land/Sales	ConstrInProg/Sales	Other/Sales
Carbon Intensity	0.529***	0.479***	-0.012	-0.017***	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
r2	0.239	0.208	0.327	0.298	0.216	0.149	0.092
N	8,206	8,206	8,206	8,206	8,206	8,206	8,206
Dep Var Mean	0.532	0.309	0.105	0.037	0.021	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.5. Tangibility, debt, tax shield, taxes and carbon emissions - Industry effects

	(1)	(2)	(3)	(4)
	PPE/Sales	Debt/Sales	Tax Shield/Sales	Taxes/Sales
Implied Industry Carbon Intensity	0.819***	0.328***	6.868***	-6.983***
	(0.081)	(0.050)	(1.064)	(1.010)
Firm Residual Carbon Intensity	0.242***	0.120***	2.086***	-2.040**
	(0.078)	(0.028)	(0.643)	(0.852)
HQ State x Year FE	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y
r2	0.361	0.165	0.214	0.193
N	13,775	13,775	13,775	13,775

Note: This table presents estimates from pooled OLS specifications of firms' tangibility, leverage, tax shield and corporate taxes paid over sales 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. (SIC4) 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. 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. Tangibility, debt, tax shield, taxes and carbon emissions - Energy sector

	(1) Carbon/Sales	(2) PPE/Sales	(3) Debt/Sales	(4) Tax Shield/Sales	(5) Taxes/Sales
Panel A:	Carbon intensity				
Carbon Intensity		0.278^{***}	0.118^{***}	2.648^{***}	-2.898^{**}
(tonnes of CO_2 per k. Sales)		(0.043)	(0.031)	(0.712)	(1.214)
Year FE		Y	Y	Y	Y
Firm Controls		Y	Y	Y	Y
r2		0.559	0.294	0.335	0.236
N		969	969	969	969
Panel B:	Fossil fuel energy production capacity				
Fossil Fuel Capacity/Sales	0.609^{***}	0.190^{***}	0.090^{***}	2.262^{***}	-2.748^{***}
	(0.078)	(0.051)	(0.023)	(0.536)	(0.841)
Year FE	Y	Y	Y	Y	Y
Firm Controls	Y	Y	Y	Y	Y
r2	0.637	0.448	0.216	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 corporate taxes paid over sales 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 megawatts 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. The firm-level statutory tax rate is the weighted average of the domestic and foreign tax rate. The domestic tax rate is the federal tax rate plus the weighted-average state-level tax rate faced by firms depending on the location of firms' employees and sales across U.S. states. The foreign tax rate is the sales weighted average country-level tax rate. 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 by firm are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1%, respectively.

B Appendix: Proofs

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

$$\sum_i \int_{\mathcal{I}(f)=i} p_{f,t} c_{f,t} df,$$

subject to achieving some level of aggregate consumption $C_t = \prod_{i=1}^{N} c_{i,t}^{\theta_i}$. We obtain the standard demand schedule

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

where $i = \mathcal{J}(f)$ denotes firm i's sector and where $p_{i,t} \equiv \left(\int_{\mathcal{I}(f)=i} p_{f,t}^{1-\sigma_i} df\right)^{\frac{1}{1-\sigma_i}}$ is the appropriate sector-level price index. In addition, the Cobb-Douglas specification implies

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

where we normalize $P_t \equiv \prod_i (p_{i,t}/\theta_i)^{\theta_i} = 1$. The latter coincides with (10).

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 (11). 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

$$\varphi_t Q_{i,t} = \varphi_{t+1}(1-\rho_i-\lambda_i)(1-\tau_d)(d_{i,t+1}+Q_{i,t+1}) + \varphi_{t+1}\tau_d Q_{i,t}.$$

Combining the first two conditions, we obtain

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

which coincides with (12). Similarly, the first and third conditions give

$$r^e_{i,t+1} \equiv \frac{d_{i,t+1}+Q_{i,t+1}}{Q_{i,t}} - 1 = \frac{(\rho_i+\lambda_i)(1-\tau_d)+(1-\tau_h)r_t}{(1-\rho_i-\lambda_i)(1-\tau_d)} \equiv r_t + \xi^E_i, \tag{B.5}$$

which is (13).

Note that the expected net return on equity is

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

thus, it coincides with the net risk-free return. An analogous condition holds for corporate bonds.

Firms. We now turn to the firm problem. In the main text, to ease notation we considered the representative firm in each sector, removing explicit reference to a specific firm within the sector. Here, we focus on the problem of the generic firm f in sector $i = \mathcal{J}(f)$. The firm maximizes

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

subject to *(i)* the process for dividends

$$d_{f,t} = (1-\tau_p)TI_{f,t} - \sum_{s\in\mathcal{T}} q^s_{i,t}(k^s_{f,t+1}-k^s_{f,t}) + b_{f,t+1} - b_{f,t}, \tag{B.6}$$

taxable income

$$TI_{f,t} = p_{f,t}y_{f,t} - \sum_{j\in\mathcal{N}} p_{j,t}x_{f,j,t} - w_t\ell_{f,t} - \sum_{s\in\mathcal{T}} \bar{\delta}_i^s q_{i,t}^s k_{f,t}^s - \sum_{s\in\mathcal{I}} q_{i,t}^s I_{f,t}^s - \sum_{s\in\mathcal{S}} \tau_k^s q_{i,t}^s k_{f,t}^s - \omega_r r_{i,t}^b b_{f,t}, \quad \text{(B.7)}$$

where $\omega_r = 1$ when interest expenses enjoy a tax shield and $\omega_r = 1/(1-\tau_p)$ otherwise; *(ii)* the production function

$$y_{f,t} = z_{i,t}\zeta_i\Big(\prod_{j\in\mathcal{N}} x_{f,j,t}^{\alpha_{ij}}\Big)^{1-\gamma_i}\Big(\ell_{f,t}^{\phi_i^\ell}\prod_{s\in\mathcal{S}}(k_{f,t}^s)^{\phi_i^s}\Big)^{\gamma_i}; \quad \text{(B.8)}$$

(iii) the law of motion for capital

$$k_{f,t+1}^s = (1-\bar{\delta}_i^s)k_{f,t}^s + I_{f,t}^s, \quad \text{(B.9)}$$

where investment is given by

$$I_{f,t}^s = \prod_{j\in\mathcal{N}}(i_{f,j,t}^s)^{\omega_{ij}^s}; \quad \text{(B.10)}$$

(iv) the borrowing constraint

$$b_{f,t+1} \leq \frac{1}{1+r_{i,t+1}^b}\sum_{s\in\mathcal{S}}\psi_{i,s}q_{i,t+1}^s k_{f,t+1}^s; \quad \text{(B.11)}$$

(v) and the demand schedule

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

where $q_{i,t}^s$ is the price of the investment bundle in type-s capital for sector i, which we define below. Note that monopolistic competitive firms take demand for their goods into account when choosing production, this is why (B.12)—which follows from (B.1) using goods-market clearing—enters the maximization problem.

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

$$\mu_i\gamma_i\phi_i^\ell = \frac{w_t\ell_{f,t}}{p_{f,t}y_{f,t}}. \quad \text{(B.13)}$$

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

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

In a symmetric equilibrium all firms in a sector make the same choices, thus, the latter two conditions become (15) and (16), respectively. Finally, conditional on total investment $I^s_{f,t}$ in type-s capital, the optimal choice of $i^s_{f,j,t}$ is static and satisfies the first-order condition

$$p_{j,t}i^s_{f,j,t} - \lambda^s_{f,t}\omega_{ij}I^s_{f,t} = 0,$$

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

$$\sum_{j\in\mathcal{N}} p_{j,t}i^s_{f,j,t} = q^s_{i,t}I^s_{f,t},$$

where $q^s_{i,t} \equiv \prod_j (p_{j,t}/\omega^s_{ij})^{\omega^s_{ij}}$ is the price index of sector i's investment bundle. Therefore,

$$i^s_{f,j,t} = q^s_{i,t}\omega^s_{ij}I^s_{f,t}\frac{1}{p_{j,t}}. \tag{B.15}$$

In a symmetric equilibrium, (B.15) becomes (17).

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, if given the choice, firms will 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 $I^s_{f,t}$ into (B.6), the optimal choice of $k^s_{f,t+1}$, in a symmetric equilibrium, satisfies the first-order condition

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

where we have used (B.5). The latter condition can be rewritten as

$$\mu_i \gamma_i \phi_i^s = R_{i,t}^s \frac{q_{i,t}^s k_{i,t}^s}{p_{i,t} y_{i,t}}, \tag{B.16}$$

where

$$R_{i,t}^s \equiv \bar{\delta}_i^s + \tau_k^s + \omega_r r_{i,t}^b \frac{\psi_{i,s}}{1 + r_{i,t}^b} + \frac{1}{1-\tau_p} r_t^e \Big(1 - \frac{\psi_{i,s}}{1 + r_{i,t}^b}\Big) + \frac{1}{1-\tau_p}(1 + r_{i,t}^e)\Big(\frac{q_{i,t-1}^s}{q_{i,t}^s} - 1\Big).$$

is the appropriate rental rate of type s capital. When $\omega_r = 1$ (i.e., interest expenses enjoy a tax shield) the latter becomes (19).

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

$$x_{j,i} = \mu_j y_j (1 - \gamma_j) \alpha_{ji} \frac{\theta_j c_i}{c_j \theta_i}. \tag{B.17}$$

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 equation (B.16) simplifies into

$$\mu_i \gamma_i \phi_i^s = R_i^s \frac{q_i^s k_i^s}{p_i y_i},$$

where the steady-state rental rate is

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

Combining the latter with (B.15) yields

$$\frac{p_j i_{i,j}^s}{p_i y_i} = \mu_i \gamma_i \phi_i^s \omega_{ij}^s \frac{\bar{\delta}_i^s}{R_i^s}. \tag{B.18}$$

Using equation (B.2) with (B.18) we obtain

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

or

$$i_{j,i}^s = \mu_j \gamma_j \phi_j^s \omega_{ji}^s \frac{\bar{\delta}_j^s}{R_j^s} y_j \frac{\theta_j c_i}{c_j \theta_i}. \tag{B.19}$$

Summing across goods and types of capital,

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

Using the resource constraint (9) yields

$$y_i = c_i + \frac{c_i}{\theta_i} \sum_{j \in \mathcal{N}} \mu_j y_j (1 - \gamma_j) \alpha_{ji} \frac{\theta_j}{c_j} + \frac{c_i}{\theta_i} \sum_{s \in \mathcal{S}} \sum_{j \in \mathcal{N}} \mu_j y_j \gamma_j \phi_j^s \omega_{ji}^s \frac{\bar{\delta}_j^s}{R_j^s} \cdot \frac{\theta_j}{c_j}. \tag{B.20}$$

It is convenient to rewrite the expressions using 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.20) 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 $\Delta \equiv A' \operatorname{diag}(\boldsymbol{\mu}) \operatorname{diag}(\boldsymbol{1} - \boldsymbol{\gamma}) + \sum_s (\Omega^s)' \operatorname{diag}(\boldsymbol{\mu}) \operatorname{diag}((\boldsymbol{R}^s)^{-1}) \operatorname{diag}(\bar{\boldsymbol{\delta}}^s) \operatorname{diag}(\boldsymbol{\phi}^s) \operatorname{diag}(\boldsymbol{\gamma})$. Thus, letting $I_{\mathcal{N}}$ denote the identity matrix of dimension $|\mathcal{N}| \times |\mathcal{N}|$,

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

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

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

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

$$\operatorname{diag}(\boldsymbol{\theta})\operatorname{diag}(\boldsymbol{c})^{-1}\boldsymbol{y} = (I_{\mathcal{N}} - \Delta)^{-1}\boldsymbol{\theta}. \tag{B.21}$$

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

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

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 (9) and equation (B.21) yields

$$\begin{aligned} L = \mathbf{1}'\boldsymbol{\ell} &= \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} (\boldsymbol{\phi}^{\ell})' \operatorname{diag}(\boldsymbol{\mu})\operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\theta})\operatorname{diag}(\boldsymbol{c})^{-1}\boldsymbol{y} \\ &= \frac{1-\tau_h}{1+\tau_c} \cdot \frac{U'(C)C}{V'(L)} (\boldsymbol{\phi}^{\ell})' \operatorname{diag}(\boldsymbol{\mu})\operatorname{diag}(\boldsymbol{\gamma})(I_{\mathcal{N}} - \Delta)^{-1}\boldsymbol{\theta}. \end{aligned} \tag{B.22}$$

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

$$1 = z_i \zeta_i \prod_{j\in\mathcal{N}} \left(\frac{x_{i,j}}{y_i}\right)^{(1-\gamma_i)\alpha_{ij}} \left(\frac{\ell_i}{y_i}\right)^{\gamma_i \phi_i^{\ell}} \prod_{s\in\mathcal{S}} \left(\frac{k_i^s}{y_i}\right)^{\gamma_i \phi_i^s}. \tag{B.23}$$

From (B.18),

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

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

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

Finally, using $I_i^s = \bar{\delta}_i^s k_i^s$, we obtain

$$\frac{k_i^s}{y_i} = \mu_i \gamma_i \phi_i^s \frac{1}{R_i^s} \cdot \frac{\theta_i}{c_i} \prod_{j\in\mathcal{N}} \left(\frac{c_j}{\theta_j}\right)^{\omega_{ij}^s}. \tag{B.24}$$

From (B.14) and (B.13), we have

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

and

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

Therefore, substituting the last expressions into (B.23) gives

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

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

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

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,

$$\log C = \boldsymbol{\theta}' \log \boldsymbol{\theta} + \boldsymbol{\theta}'(I_{\mathcal{N}}-\Gamma)^{-1}\left[\log \boldsymbol{z} + \log \boldsymbol{\mu} + \operatorname{diag}(\boldsymbol{\gamma})\boldsymbol{\phi}^{\ell} \log\left(\frac{1-\tau_h}{1+\tau_c}\cdot\frac{U'(C)C}{V'(L)}\right) - \sum_{s\in\mathcal{S}} \operatorname{diag}(\boldsymbol{\gamma})\operatorname{diag}(\boldsymbol{\phi}^s)\log(\boldsymbol{R}^s)\right]. \tag{B.25}$$

Counterfactuals with "exact-hat algebra". We consider a change in the rental rate of 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 $\hat{R}_i^s \equiv (R_i^s)'/R_i^s$ 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 to denote changes of equilibrium variables relative to their counterparts in the original equilibrium, we can rewrite (B.13) as

$$\hat{\ell}_i = \frac{\hat{C}^{1-\sigma}}{\hat{L}^{\epsilon}}\cdot\frac{\hat{y}_i}{\hat{c}_i}, \tag{B.26}$$

where we used (B.4) to substitute in for the equilibrium wage. From labor-market clearing,

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

or, using (B.26),

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

where $\vartheta_i^L \equiv w\ell_i/wL$. Similarly, we can rewrite (B.17) and (B.19) as

$$\hat{x}_{j,i} = \hat{y}_j \frac{\hat{c}_i}{\hat{c}_j} \tag{B.27}$$

and

$$\hat{i}_{j,i}^s = \frac{1}{\hat{R}_j^s}\hat{y}_j\frac{\hat{c}_i}{\hat{c}_j}, \tag{B.28}$$

respectively. Also, from (B.24), we obtain

$$\frac{\hat{k}_i^s}{\hat{y}_i} = \frac{1}{\hat{R}_i^s}\cdot\frac{1}{\hat{c}_i}\prod_{j\in\mathcal{N}}\hat{c}_j^{\omega_{ij}^s}. \tag{B.29}$$

The resource constraint (9) then becomes

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

or, using (B.17) and (B.19) with (B.27) and (B.28),

$$\frac{\hat{y}_i}{\hat{c}_i} = \vartheta^C_i + \sum_{j\in\mathcal{N}} \mu_j \alpha_{ji}(1-\gamma_j)\vartheta^Y_{ji}\frac{\hat{y}_j}{\hat{c}_j} + \sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}} \mu_j\gamma_j\phi^s_j\omega^s_{ji}\frac{\bar{\delta}^s_j}{R^s_j}\vartheta^Y_{ji}\frac{1}{\hat{R}^s_j}\cdot\frac{\hat{y}_j}{\hat{c}_j}, \tag{B.30}$$

where we let $\vartheta^C_i \equiv p_i c_i/p_i y_i$ and $\vartheta^Y_{ji} \equiv p_j y_j/p_i y_i$.

Also, using (B.26), (B.27) and (B.29), we can rewrite (B.23) as

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

or, taking logs of both sides,

$$\log\hat{c}_i = \sum_{j\in\mathcal{N}}(1-\gamma_i)\alpha_{ij}\log\hat{c}_j + \gamma_i\phi^\ell_i\log\frac{\hat{C}^{1-\sigma}}{\hat{L}^{\epsilon}} - \sum_{s\in\mathcal{S}}\gamma_i\phi^s_i\log\hat{R}^s_i + \sum_{s\in\mathcal{S}}\sum_{j\in\mathcal{N}}\gamma_i\phi^s_i\omega^s_{ij}\log\hat{c}_j. \tag{B.31}$$

Finally, from the definition of aggregate consumption,

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

and, thus,

$$\log\hat{C} = \sum_{i\in\mathcal{N}} \theta_i \log\hat{c}_i. \tag{B.32}$$

The relative change in inputs, output and consumption in the counterfactual economy are thus described by (B.26), (B.27), (B.28), (B.29), (B.30), (B.31) and (B.32).

B.1 Proofs for Section 4.3 and Section 4.4

Let the firm's cost function be

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

subject to

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

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

$$1 = \mathcal{F}_i\left(z_i, \left\{ \frac{\tilde{x}_{fj,t}}{y_{f,t}} \right\}_j, \frac{\tilde{\ell}_{f,t}}{y_{f,t}}, \left\{ \frac{\tilde{k}^s_{f,t}}{y_{f,t}} \right\}_s \right),$$

for any value of $y_{f,t}$. It is thus sufficient to solve the problem for $y_{f,t} = 1$ and then scale the solution by $y_{f,t}$. We therefore have

$$\begin{aligned}
\mathcal{C}_f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s, y_{f,t}) &= \Big(\sum_{j\in\mathcal{N}} p_{j,t}x_{f,j,t} + w_t\ell_{f,t} + \sum_s R^s_{i,t}q^s_{i,t}k^s_{i,t} + \tau_e e_i \Big) y_{f,t} \\
&\equiv \mathcal{MC}_f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s) y_{f,t},
\end{aligned}$$

where choice variables without a tilde denote the solution to the firm's problem corresponding to $y_{f,t} = 1$. The function $\mathcal{MC}_f$ represents the firm's marginal cost curve.

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

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

subject to

$$y_{f,t} = \left(\frac{p_{f,t}}{p_{i,t}} \right)^{-\sigma_i} y_{i,t}. \tag{B.33}$$

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

The first-order condition is

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

or, rearranging,

$$(1-\hat{\tau}_f)p_{f,t} = \frac{1}{\mu_i}\mathcal{MC}_f(w_t, \{p_{j,t}\}_j, \{R_t^s\}_s). \tag{B.34}$$

Taking the logarithm of the price equation (B.34) and differentiating it with respect to $R_{i,t}^s$ gives

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

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

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

We conclude that

$$\frac{\partial \log p_{f,t}}{\partial R_{i,t}^s} = \frac{1}{\mu_i(1-\hat{\tau}_f)} \cdot \frac{q_{i,t}^s k_{f,t}^s}{p_{f,t}y_{f,t}}. \tag{B.35}$$

Having computed the percentage change in price, we can compute the percentage change in firm's emissions $\partial \log E_f/\partial R_{i,t}^s$. Since $E_f = e_i y_{f,t}$, the latter is the same as the percentage change in output $\partial \log y_{f,t}/\partial R_{i,t}^s$. Using the demand equation (B.33), we conclude that

$$\frac{\partial \log y_{f,t}}{\partial R_{i,t}^s} = -\sigma_i \frac{\partial \log p_{f,t}}{\partial R_{i,t}^s}. \tag{B.36}$$

Consider now the policy that removes the tax shield. 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.35) and (B.36) yields the total differential

$$d\log E_{f,t} = -\sigma_i \times \frac{1}{\mu_i(1-\hat{\tau}_f)}\sum_{s\in\mathcal{S}}\frac{q_{i,t}^s k_{f,t}^s}{p_{f,t}y_{f,t}} \times \frac{\tau_p}{1-\tau_p}r_{i,t}^b\frac{\psi_{i,s}}{1+r_{i,t}^b}. \tag{B.37}$$

In steady state, the latter coincides with (21).

Analogous steps prove that

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

and, thus, (22):

$$d\log E_{f,t} = -\sigma_i \times \frac{1}{\mu_i(1-\hat{\tau}_f)} \cdot \frac{E_{f,t}}{p_{f,t}y_{f,t}} \times \tau_e. \tag{B.38}$$

We are left to prove the equivalence between the tax shield policy and a policy comprising a carbon tax and a revenue tax. For simplicity, we focus on steady-state variables and drop time subscripts. First, notice that the arguments above also prove that the price effect of a change in the revenue tax is

$$\frac{\partial \log p_f}{\partial \hat{\tau}_f} = \frac{1}{1-\hat{\tau}_f}$$

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

$$d\log E_{f,t} = -\sigma_i \times \frac{1}{1-\hat{\tau}_f} \times \hat{\tau}_f. \tag{B.39}$$

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

$$\sum_{s\in\mathcal{S}} q_i^s k_f^s \frac{\tau_p}{1-\tau_p} r_i^b \frac{\psi_{i,s}}{1+r_i^b} = \frac{\tau_p}{1-\tau_p} r_i^b b_f \equiv \frac{1}{1-\tau_p} TS_f,$$

where the last line uses the definition of tax shield given in the main text. It follows that we can rewrite (B.37) as follows:

$$d\log E_f = -\sigma_i \frac{1}{\mu_i(1-\hat{\tau}_f)(1-\tau_p)} \cdot \frac{TS_f}{p_f y_f}.$$

or, using the decomposition (23),

$$d\log E_f = -\sigma_i \frac{1}{\mu_i(1-\hat{\tau}_f)(1-\tau_p)} \Big(\beta \frac{E_f}{p_f y_f} + \epsilon_f\Big).$$

Finally, using (B.38) and (B.39) the latter can be seen as the effect of a policy combining a carbon tax $\tau_e = \beta/(1-\tau_p)$ and a revenue tax $\hat{\tau}_f = \epsilon_f/\mu_i(1-\tau_p)$.