Asset returns as carbon taxes*

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Abstract

In frictionless financial markets, a carbon tax on energy users provides the same incentives as a *replicating return schedule* that depends on firms' emission intensities, defined as scope 1 emissions relative to enterprise value. We use this result to interpret pollution premia measured by recent empirical studies and conclude that markets currently provide only modest incentives. Replicating a serious carbon tax requires high returns in the right tail of the emission intensity distribution. With heterogeneous investors, such returns are not sustainable unless essentially everyone perceives large nonpecuniary costs from holding dirty capital. Substantial emission reductions can be achieved, however, when even a small share of investors perceive nonpecuniary *benefits* from owning clean electricity capital.

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1 Introduction

A large fraction of wealth in modern financial markets is invested in green assets.[1] In theory, green investing can affect the real economy by altering firms' costs of capital. If investors demand higher expected returns—pollution premia—on dirtier firms, it becomes more expensive for such firms to raise capital, and they should grow more slowly. A growing empirical literature measures return differentials between dirty and clean firms. While the results are not yet clear-cut, in part because the available time series are short, there is mounting evidence of a positive pollution premium. At the same time, survey evidence shows that a substantial fraction of households is willing to give up some returns to benefit the environment. What is unclear, however, is how strong these preferences for green assets must be for this to have an impact.

This paper asks what it takes for capital markets to mimic a carbon tax, the standard tool economists recommend to fix a climate externality. We first show that, in a large class of models with frictionless firm financing, a carbon tax on energy users provides the same incentives as a *replicating return schedule* that depends linearly on a firm's emission intensity, defined as scope 1 emissions relative to enterprise value. By evaluating replicating return schedules at emission intensities currently observed in the U.S. economy, we show that financial markets today provide at most modest incentives, equivalent to a carbon tax on the order of \$10 per ton of CO_2. Computing replicating returns in a quantitative GE model shows that a \$100-per-ton carbon tax requires large returns on dirty production plans. The model allows for heterogeneous preferences: if not all agents are green investors, exact replication is no longer possible, but we still can ask what return schedules can get close to what a carbon tax would accomplish.

The idea behind the equivalence result is that a proportional tax on scope 1 emissions at rate τ_c leads to the same allocation as a tax on capital with rate *schedule* $(\tau_c E/K)$ that rises linearly with the emission intensity E/K. Both tax schemes impose the same tax burden $\tau_c E = (\tau_c E/K)K$, paid by emitting firms under a carbon tax, and by investors under a capital tax. However, a capital tax implies cross-sectional differences in returns—or costs of capital—across firms based on emission intensity: investors in dirtier firms require more compensation for higher tax rates. Firms' incentives to choose production plans are then the same whether they pay carbon tax directly or indirectly via the cost of capital.

A similar equivalence result applies when return differences arise not from capital taxes but from investor preferences—specifically, from nonpecuniary costs that a representative investor associates with holding dirty capital. In both cases, a carbon tax *rate* corresponds to a return *schedule*, whereas the cross-section of replicating returns consistent with a carbon tax rate depends on the endogenous choice of intensities. Like the tax burden, equilibrium returns reflect not only the tax rate, but also features of the economic environment such as technology. For example, technical progress that makes it cheaper to save energy will lower equilibrium returns consistent with replication of a given carbon tax rate.

[1] According to Bloomberg Intelligence, global ESG assets are currently roughly 20% of assets under management and are projected to increase to 25% of assets under management by 2030.

To illustrate the magnitude of replicating returns, we conduct two quantitative exercises. First, we evaluate return schedules at the currently observed cross-section of emission intensities. For any given carbon tax rate, the resulting distribution describes returns that we would see today if financial markets were replicating the tax. A \$10 carbon tax requires premia for emissions that are 6 basis points on average but the right-skewed distribution of emission intensities implies much higher premia at the top: 60bp at the 99th percentile. For publicly traded electricity companies, the median premium is 1 percent, while the 90th percentile reaches 1.6%. Since the empirical asset pricing literature typically finds pollution premia of only a few percentage points, we conclude that the current financial market incentives are modest.

Our second exercise evaluates return schedules at emission intensities that emerge in equilibrium after firms have adjusted to a high carbon tax. The resulting return distributions reflect the capital tax rates—or the nonpecuniary costs—that investors would need to bear to enforce strong climate incentives. To predict these adjustments, we use a multisector growth model with a detailed energy sector, calibrated using both sector-level data and firm-level data from the electricity sector. Under a \$100 carbon tax, the return premia become substantial in the right tail of the distribution: the 99th percentile reaches 5%, with high premia in the transport sector, which has limited ability to substitute away from oil. In contrast, electricity firms, which can more easily substitute away from coal, face much lower premia—just 21 bp at the median and 1.1% at the 90th percentile. In this sector, most adjustment occurs within firms: the replicating return schedule incentivizes currently dirty firms to clean up their production.

Importantly, these incentives are provided by the entire return schedule—not just by equilibrium returns. For example, an electricity firm considering a production plan with today's median emission intensity would face a 10% premium under a \$100 carbon tax. To replicate such a return schedule based on investor preferences, *all* investors must incur large nonpecuniary costs from holding dirty capital and therefore be willing to sacrifice substantial pecuniary returns. This motivates an extension of our model to heterogeneous investors who face short-sale constraints. We assume that green investors interact with traditional investors who do not care about the emission intensity of their portfolio.

When green investors incur nonpecuniary costs, even a small presence of traditional investors greatly weakens the impact of green investing on emissions. Starting from a scenario in which 100% of wealth is held by green investors whose preferences replicate a \$100 carbon tax, the introduction of just 2% of wealth held by traditional investors is enough to undo half of the emission reduction. This fragility arises for two key reasons: (i) the distribution of emissions is heavily right-skewed, and (ii) many of the dirtiest firms also have the greatest potential to reduce their emission intensities. In equilibrium, traditional investors sort into holding these high-emission firms—those that green investors avoid due to high nonpecuniary costs—and are happy to accept the same returns from all of them. The resulting return schedule is flat at the highest intensities, where strong incentives are most needed.

Can a small share of green investors still generate meaningful incentives for emission reduction? Suppose instead that investors derive a *nonpecuniary benefit from holding electricity firms*, and more so the lower their emission intensities. We show that if just 2% of wealth is held by investors who are willing to forgo less than 2% of wealth per year in equilibrium, they can achieve about one-quarter of the emission reductions of a $100 carbon tax. While traditional investors still hold firms that green investors find expensive and charge them the same returns, these firms are often already clean, so the lack of incentives is irrelevant. Green investors end up subsidizing electricity firms, including some dirtier ones, but because the subsidy declines with emission intensity, incentives are concentrated where they are most effective.

We take away from these exercises that the marketing of green investment products should change. The current emphasis on negative screening, akin to a divestment campaign that punishes dirty firms with high costs of capital, is misguided. Instead, green investing should aim to incentivize emission reductions, especially in sectors that are currently dirty but can adjust. In our model, we quantify the effectiveness of different investment strategies by comparing alternative preferences by green investors. This approach is helpful because preferences for green products are still evolving and shaped in part by what products intermediaries offer. As green investing remains relatively new, there is both a strong demand for products that help reduce emissions, but no clear understanding about which approaches are most effective.[2]

To see how our equivalence result works formally, compare a carbon tax on fossil fuel use to a tax on equity that rises with emission intensity. With a tax on equity in place, investors and firms distinguish stocks by the emission intensities of the firms that issue them. We thus consider a continuum of markets for stocks indexed by emission intensity. When households choose portfolios to maximize utility, they price in return differentials that compensate them for the capital tax. Investor optimality thus implies a return *schedule* for a cross-section of equity markets that differ by convenience yields, here due to tax treatment. This replicating return schedule is independent of the production side of the economy.

It is crucial for the result that emission intensities are endogenous: firms choose intensities as part of production plans that include fossil fuel inputs. Equilibrium matches households' asset demand, that is, the return schedule, with firms that maximize shareholder value. The distributions of returns and emission intensities are then jointly determined: technologies are funded via those markets where they achieve the highest value. To this end, firms' choice of production plans takes into account shareholders' required after-tax rate of returns, which depend on the emission intensity. In particular, when the tax rate per dollar of equity rises linearly with intensity, then the tax bill—equity multiplied by the tax rate—becomes independent of the value of equity and enters the firm's problem exactly like the carbon tax bill.

The replicating schedule need not literally come from capital taxes. Consider instead a representative investor with utility over consumption less a nonpecuniary cost that is linear in emissions by firms in the portfolio. We obtain the same allocation as when carbon tax revenue is wasteful government spending. On the firm side, the equivalence result requires shareholder

[2]We note that a nonpecuniary benefit for electricity shares features of a preference for *changes* in emissions, and hence some scoring rules developed in the financial sector. In particular, it rewards dirty firms to become cleaner. There is a subtle difference, however: if clean electricity is mostly produced by entrants that always have zero emissions, our scheme subsidizes them even though their intensities never change.

value maximization but no specific assumptions on technology or market structure. It is thus robust to many extensions, including heterogeneous capital goods, risk from productivity or preference shocks, or adjustment costs to capital. It also holds in the presence of rents from product market power or distortionary taxes. Our approach can therefore be applied to compute replicating returns implied by most existing computable general equilibrium models used to study environmental policy.

Since asset demand in our model defines a return schedule, it provides an incentive scheme, and not simply a penalty on currently dirty firms. The incentive scheme rewards substitution within firms just like substitution across firms. In fact, the former drives a large share of emission reductions in our quantitative exercises, especially in the electricity sector. The equivalence result requires no assumptions about the boundaries of the firm. It does not matter, for example, whether greener production occurs in specific firms or in large conglomerates that also engage in a lot of dirty production. As with a carbon tax, decarbonization may occur because clean firms grow at the expense of dirty firms since their cost of capital is lower or because initially dirty firms transform themselves by cleaning up their production in order to enjoy a lower cost of capital.

All of our results assume that scope 1 emissions can be measured and are public information. Whether incentives come from a capital tax or investor preferences, the emission intensity relative to the value of the firm must be verifiable by the tax authority or investors, respectively. We view this as a relatively low burden. For large companies, measures of scope 1 emissions are already available from multiple data vendors, including the TruCost data we use for our calibration of the power sector. The SEC's March 2024 rule, currently inactive, requires that public companies disclose an estimate of scope 1 emissions with quarterly filings. We also note that our results rely only on emissions generated by fossil fuel use, which are arguably even easier to measure since they are directly related to purchases of inputs.

Our results also say that the scoring of firms for climate impact should focus on scope 1 emissions only, and do not require measurement or disclosure of more complicated concepts of emissions. The equivalence result equates a return schedule based on scope 1 intensity to a carbon tax on energy *use*. The return schedule should therefore not penalize energy producers for the dirty fuels they produce—part of their scope 3 emissions—but only for scope 1 emissions that arise in production. The argument is analogous to the principle that externalities can be taxed at the producer or user level, but taxing both does not make sense. Similarly, as long as electricity producers' cost of capital responds to their scope 1 emission intensity, it is not necessary to measure electricity users' scope 2 emissions.

Related literature. Our modeling framework builds on the long tradition of general equilibrium integrated assessment models designed to assess policies such as carbon taxes.[3] Since our objective is to compare tax schemes and investor preferences—rather than to compute optimal tax rates—we keep the climate side of the model simple and only minimally capture a climate

[3]See Nordhaus 2013 for a historical survey and IAMC (2025 website) for an overview of models currently used around the world.

externality. We share the focus on one country that engages in international trade with climate models of the U.S. economy, for example Goulder and Hafstead (2017), Yuan et al. (2019) and models reviewed in a meta-study on carbon tax scenarios for the U.S. by the Energy Modeling Forum (EMF, see McFarland et al. 2018). In particular, we also specify an input-output structure that allows tax effects to propagate through supply chains. For the electricity sector, we further incorporate firm-level heterogeneity to model substitution, in the spirit of detailed "bottom-up" models used in energy economics. Since there is considerable uncertainty about technology parameters such as long-run substitution elasticities, we benchmark our predictions for emissions, energy and macro aggregates to the EMF study — we obtain results that they are broadly similar to the typical model in the literature.

A number of other papers examine the relationship between carbon taxes and the cross-section of returns in financial markets. Iovino et al. (2024) analyze how capital taxation affects an economy's carbon footprint through capital reallocation. Papoutsi et al. (2024) study reallocation driven by the cross-sectional effects of unconventional monetary policy, focusing on the ECB's corporate bond purchase program. Pedersen (2024) compares carbon taxes to return differentials under various assumptions on firm objectives. A key difference between our setup and these papers is the concept of equilibrium: we emphasize that when investors distinguish stocks by emission intensity, capital market equilibrium involves a cross-section of markets that clear to jointly determine prices and properties of traded assets, here emission intensities.[4] This is what leads to a very general equivalence result.

Our return schedule provides a benchmark to interpret evidence on pollution premia—that is, cross-sectional differences in mean returns, and hence costs of capital, between dirty and clean firms. Across various measurement approaches, the estimated pollution premia tend to be modest—typically no more than a couple of percentage points—and thus far insufficient to provide strong incentives to the dirtiest firms. Hong and Shore (2023) survey a large literature attempting to estimate these premia from asset return data. A key empirical challenge is that the ongoing transition toward greener investment makes it hard to estimate mean returns (Pástor, Stambaugh and Taylor 2021). Studies based on investor surveys reach similar conclusions on mean returns, while also highlighting considerable heterogeneity in preferences (for example, Riedl and Smeets 2017, Giglio et al. 2025, Aron-Dine et al. 2024). The most direct evidence on the channel we are interested in comes from Gormsen, Huber and Oh (2024), who infer managers' perceptions of costs of capital from corporate conference calls. Their findings highlight, in particular, that managers of utility companies perceive lower costs of capital for their cleaner divisions, consistent with the within-firm substitution effect in our model.

Our results on equilibria with investor tastes contribute to a growing literature on climate

[4]This theme is familiar from other work. For example, Fostel and Geanakoplos (2015) study models with collateral constraints where markets clear to jointly determine interest rates and the default risk of the borrower. Rogerson et al. (2005) survey competitive search models where prices are determined jointly with market tightness, and thus the queue length of the seller. In our context, assets differ in endogenously determined convenience yields that reflect the emission intensity of the issuer.

finance with heterogeneous investors (for an overview, see Pastor et al. 2024).[5] Early work focused on *negative screening*, where some investors exclude some assets from their portfolios and accept higher risk as a result (Heinkel et al. 2001; Geczy et al. 2021). Berk and van Binsbergen (2021) show that if only few investors apply such screens, the aggregate impact of climate finance is quantitatively small. By contrast, we model green investors as deriving *convenience yields* from their green assets, as in Pástor, Stambaugh and Taylor (2021), Pedersen, Fitzgibbons and Pomorski (2021), or Aron-Dine et al. (2024). While those papers study asset pricing and portfolio tilts, we focus on implications for real outcomes—specifically, emissions—in a production economy. We further establish that nonpecuniary *benefits* are particularly powerful because they reflect a willingness to subsidize green firms through lower costs of capital. By contrast, nonpecuniary costs imply higher returns for dirty assets, which are easier to erode when a small share of investors are indifferent to holding them.

The paper is structured as follows. Section 2 introduces a model with a representative agent and standard preferences and shows the equivalence between a carbon tax and a capital tax with a rate that responds to emission intensity. Section 3 presents our data and a first set of quantitative results: replicating returns when intensities do not adjust. Section 4 discusses the calibration of the model and derives equilibrium returns. Section 5 extends the model to allow for nonpecuniary benefits and costs as well as heterogeneous investors and presents quantitative results for this case.

2 Model

We consider a standard growth model with an input-output structure and climate externalities. We first lay out a physical environment and introduce a simple system of markets for which we show our equivalence result. For transparency, we abstract from a number of interesting frictions. We then discuss how the equivalence result holds for alternative decentralizations as well as extensions of the environment.

2.1 Physical environment

Preferences. A representative household lives forever, inelastically supplies one unit of labor and values a consumption good C_t as well as the state of the environment, summarized by the cumulative sum of emissions η_t. Preferences are represented by utility

$$\sum_{t=0}^{\infty} \beta^t \left(u \left(C_t \right) - v \eta_t \right), \tag{1}$$

where $v > 0$. This is a minimal way to introduce a climate externality. The precise nature of damages is not important for our exercise since we take the size of the carbon tax as given.

[5]We follow most of this work in assuming *non-consequentialist* preferences, that is, investors like clean assets for private reasons, not because of their aggregate real effects, consistent with the evidence in Bonnefon et al. (2025) and Heeb et al. (2023).

Technology. Production of the consumption good C_t uses a vector of N intermediate goods y_t where, $n \in \mathcal{N} := \{1, \ldots, N\}$. Intermediate good n is made from labor l_t^n, capital k_t^n, a collection of intermediate goods x_t^n and $\tilde{N}$ foreign goods collected in a vector $\tilde{x}_t^n$. The economy exports a good $\tilde{Y}_t$ made from intermediates. There are also N capital goods, one specific to each intermediate good, with capital good n made from intermediates collected in a vector z_t^n. Capital can be first used one period after it has been installed and depreciates at rate δ_n in sector n. Production functions for all goods are homogeneous of degree one in inputs.

Technology is described by the production functions g, $\tilde{g}$, h^n, and f^n for the consumption good, the export good, the nth capital good, and the nth intermediate good, respectively. The resource constraints are

$$\begin{aligned} C_t &= g\left(y_t\right), \\ \tilde{Y}_t &= \tilde{g}\left(\tilde{y}_t\right), \\ k_{t+1}^n &= \left(1-\delta_n\right) k_t^n + h^n\left(z_t^n\right), \qquad n \in \mathcal{N} \\ y_{t,n} + \tilde{y}_{t,n} + \sum_{j \in \mathcal{N}} \left(x_{t,n}^j + z_{t,n}^j\right) &= f^n\left(l_t^n, k_t^n, x_t^n, \tilde{x}_t^n\right), \qquad n \in \mathcal{N}. \end{aligned} \tag{2}$$

The last equation is the resource constraint for intermediate good n. The production of good n is used for consumption $y_{t,n}$, export goods $\tilde{y}_{t,n}$, other intermediates $x_{t,n}^j$ and investment $z_{t,n}^j$.

Emissions. The production of intermediate goods generates emissions. We use an emission function e^n to indicate how many emissions are generated for every production plan in sector n. The evolution of the state of the environment can then be written as

$$\eta_t = \eta_{t-1} + \sum_{n \in \mathcal{N}} e^n\left(l_t^n, k_t^n, x_t^n, \tilde{x}_t^n\right) + \tilde{e}_t, \tag{3}$$

where $\tilde{e}_t$ is an exogenous sequence that represents foreign emissions. For many sectors, pollution can be described by an emission function that is linear in fossil fuel inputs, elements of x_t or $\tilde{x}_t$. However, some emissions are generated by the interaction of intermediates and capital, for example feed and animals in agriculture. Our convention that production of consumption, export and capital goods does not generate emissions is not restrictive since we can always define additional intermediates.

International trade. The country takes as given prices of imported goods collected in a vector $\tilde{p}_t$. We abstract from foreign borrowing and assume that trade is balanced every period. We thus require that the value of imports of foreign goods purchased by all intermediate sectors equals the value of output of the export good:

$$\sum_{n \in \mathcal{N}} \sum_{m \in \tilde{\mathcal{N}}} \tilde{p}_{t,m} \tilde{x}_{t,m}^n = \tilde{P}_t \tilde{Y}_t. \tag{4}$$

Social planner problem. As a benchmark, consider a social planner who cares about local citizens' welfare. The social planner maximizes utility (1) subject to technology (2), the evolution of the state of the environment (3), the trade balance (4), and the resource constraint for labor

$$\sum_{n \in \mathcal{N}} l_t^n = 1. \tag{5}$$

The optimal allocation internalizes the negative impact of dirty energy use on households' utility due to higher cumulative emissions η_t. The planner as defined here does not take into account local citizens' substitution towards emission-intensive imported goods.

Let μ_t denote the planner's multiplier on the evolution of the state of the (3). The social cost of carbon, or the shadow cost of an additional unit of emissions in units of marginal utility, is given by $SCC_t = \mu_t / u'(C_t)$. The planner equates the marginal product of any input to its total marginal cost, including its contribution to emissions valued by the social cost of carbon. For example, the planner's FOC for intermediate good j is

$$g_n'(y_t) \frac{df^n}{dx_j} (l_t^n, k_t^n, x_t^n, \tilde{x}_t^n) = \lambda_{t,j} + SCC_t \frac{de^n}{dx_j} (l_t^n, k_t^n, x_t^n, \tilde{x}_t^n) \, , \tag{6}$$

where $\lambda_{t,j}$ is the multiplier on the jth resource constraint in the last equation of (5). Standard arguments imply that a competitive equilibrium with a carbon tax rate equal to the social cost of carbon decentralizes the social optimum. Intuitively, the spot price of fuel works like the shadow cost and is augmented by the tax per unit of fuel, that is, the SCC times the emission factor.

2.2 Markets and equilibrium

We consider competitive firms owned by households and traded in frictionless financial markets. All goods are traded in competitive markets. The consumption good serves as numéraire.

Firms and equity. We assume one firm type for each production function in (2). Since firms that make the same good are all identical, we describe one representative firm per good. Producers of the consumption goods and the N capital goods exist for one period. They buy intermediate goods at prices $p_{t,n}$. Producers of the nth capital good sell at the price $p_{t,n}^k$. Intermediate goods firms exist for two periods. Firms enter at date t, raise funds by issuing equity and use those funds to purchase capital goods, both at date t . At date $t+1$, they purchase intermediates, hire labor, produce, and sell undepreciated capital. We denote by $v_{t,n}$ the cum-dividend value of a firm in sector n to shareholders at date t.

Capital and carbon taxes. The government levies a proportional carbon tax τ_t^c on firms per unit of emissions. In addition, there are taxes on households' holdings of equity. The tax rate per unit of equity depends on the emission intensity of the firm that has issued the equity. The emission intensity of a firm that is worth v_t and generates emissions e_t is

$$\varepsilon_t = \frac{e_t}{v_t}$$

The capital tax schedule applied at date t is given by a weakly increasing function $\tau_t^k(\varepsilon_t)$. In order to implement an actual tax with this schedule, the government would have to measure emissions over some period of time as well as the value of the firm at the end of that period.

Equity markets. Households save by investing in equity. Since capital taxes depend on the intensity of production at date $t+1$, firms and households at date t distinguish equity claims by their intensity ε_{t+1}. We therefore consider a continuum of equity markets indexed by ε_{t+1}. We quote prices in those markets in terms of returns: let $R_{t+1}(\varepsilon)$ denote the gross rate of return on equity of intensity ε earned by investing one unit of numéraire from date t to date $t+1$.

Household problem. An individual household takes as given the evolution of the environment η_t and maximizes utility (1) by choosing consumption and nonnegative equity holdings $s_{t+1}(\varepsilon)$ subject to the budget constraint

$$C_t + \int s_{t+1}(\varepsilon)\, d\varepsilon = \int R_t(\varepsilon)\left(1-\tau_t^k(\varepsilon)\right) s_t(\varepsilon)\, d\varepsilon + w_t + T_t, \tag{7}$$

where w_t is the wage and T_t is a lump sum transfer from the government. Here the integrals sum up over all equity markets the household can invest in. Households care about after-tax returns.

Since the problem is deterministic, after-tax returns on all equity claims must be equal. Asset prices thus satisfy the Euler equations

$$R_{t+1}(0) = \beta u'(C_t)/u'(C_{t+1}), \tag{8}$$

$$R_{t+1}(\varepsilon_{t+1})\left(1-\tau_{t+1}^k(\varepsilon_{t+1})\right) = R_{t+1}(0). \tag{9}$$

We label $R_t(0)$ the "clean rate", that is, the rate of return on equity of a firm that does not generate any emissions. Since that equity claim is not taxed, its rate of return is equal to the household's marginal rate of substitution between consumption at date t and $t+1$. Returns on other equity claims are typically higher than the clean rate to compensate investors for taxes, and more so the dirtier the firm is, in the sense of higher ε.

We note that the shape of the capital tax schedule is inherited to a close approximation by the schedule of *net* returns $r_{t+1}(\varepsilon_{t+1}) = R_{t+1}(\varepsilon_{t+1}) - 1$. As long as returns and taxes are small decimal numbers, their products are an order of magnitude smaller. We can then write (9) as

$$r_{t+1}(\varepsilon_{t+1}) - r_{t+1}(0) \approx \tau_{t+1}^k(\varepsilon_{t+1}). \tag{10}$$

In other words, the premium on a dirty firm, defined as the spread between its net return and the clean net return, is given by its capital tax rate. In particular, the case of linear capital tax rates that is central to our analysis below then implies an approximately linear return schedule. When we use language like "linear return schedule" in what follows, it is understood that this approximation holds.

Intermediate-goods firm problem. Consider a firm that makes good n with a production plan

$X = (l, k, x, \tilde{x})$, that is, a list of labor, capital, intermediates and foreign goods. For now assume that there is no carbon tax, only a tax on capital. The cum-dividend value of the firm at date $t+1$ generated by the plan is

$$v_{t+1,n}(X) = p_{t+1,n} f^n(l, k, x, \tilde{x}) - \sum_{j \in \mathcal{N}} p_{t+1,j} x_j - \tilde{p}_{t+1,j} \tilde{x}_j - w_{t+1} l + p^k_{t+1,n} k (1 - \delta_n). \tag{11}$$

Firm value equals capital income—revenue less expenditure on domestic and imported intermediates and the wage bill—plus the value of undepreciated capital.

At time t, firms maximize shareholder value by choosing a production plan X. We can restrict attention to production plans with a positive value. Any such plan implies an emission intensity $\varepsilon(X) = e^n(X) / v_{t+1,n}(X)$, which determines the equity market in which the firm can raise funds. To fund a firm in market ε, shareholders require the return $R_{t+1}(\varepsilon)$. A technology is then funded in the market where it generates the highest value, or enjoys the lowest cost of capital. The optimal production plan solves

$$\max_X \left\{ -p^k_{t,n} k + R_{t+1}(\varepsilon(X))^{-1} v_{t+1,n}(X) \right\} \tag{12}$$

Discounting reflects the emission intensity at the production plan X. Both the firm's emissions in the numerator and the value in the denominator depend on the plan.

Since households' Euler equations (9) hold in any equilibrium, we can substitute into (12) and rewrite shareholder value as

$$-p^k_{t,n} k + R_{t+1}(0)^{-1} \left(1 - \tau^k_{t+1}(\varepsilon(X))\right) v_{t+1,n}(X).$$

A firm that discounts using the cost of capital $R_{t+1}(\varepsilon)$ thus behaves like a firm that discounts using the clean rate $R_{t+1}(0)$, but pays a tax on firm value that depends on the emission intensity $\varepsilon(X)$. The decision of which production plans X to fund therefore not only takes into account profits, but also the fact that the cost of capital rises with the emission intensity.

The case of linear capital tax rates. The effect of capital taxes is particularly simple when the capital tax rate schedule is linear in the emission intensity, that is, $\tau^k_{t+1}(\varepsilon) = \bar{\tau}^k_{t+1} \varepsilon$ for some slope $\bar{\tau}^k_{t+1}$, say. In this case, we can substitute out $\varepsilon(X)$ using the definition of intensity to obtain

$$-p^k_{t,n} k + R_{t+1}(0)^{-1} \left(v_{t+1,n}(X) - \bar{\tau}^k_{t+1} e^n(X)\right). \tag{13}$$

Since emission intensity is defined relative to value, a linear tax implies that value cancels. As a result, the slope of the capital tax schedule now enters as a proportional tax on emissions, exactly like a proportional carbon tax would appear as well. This observation is the basis of our main equivalence result.

With a linear capital tax rate schedule, the firm's first-order conditions for domestic intermediate j and capital are

$$
\begin{aligned}
p_{t+1,n}\frac{df^n}{dx_j} &= p_{t+1,j} + \bar{\tau}^k_{t+1}\frac{de^n}{dx_j},\\
p_{t+1,n}\,\frac{df^n}{dk} &= p^k_{t+1,n}\left(1-\delta_n\right) - R_{t+1}\left(0\right)p^k_{t,n} + \bar{\tau}^k_{t+1}\frac{de^n}{dk},
\end{aligned}
\tag{14}
$$

respectively, where all derivatives are evaluated at the optimal production plan. First order conditions for other variable inputs, that is, labor and foreign intermediates, are analogous to the first equation: the optimal choice of a variable input equates its marginal product to its market price plus its marginal contribution to the tax bill, given by the tax rate times the marginal emission.[6]

Firms behave as if there was a carbon tax, with the tax rate on emissions given by the slope of the capital tax rate schedule. With a capital tax rate schedule that depends on the emission intensity, higher emissions increase the emission intensity and thereby the cost of capital. The special feature of a linear capital tax schedule is that the marginal effect on the cost of capital is independent of the emission intensity, it only depends on the slope. As a result, the slope of the capital tax schedule plays exactly the same role as the carbon tax rate. Indeed, if a carbon tax with rate τ^c_t, say, were present in addition to the capital tax, then profits and first order conditions would be the same except the tax rate is the sum $\tau^c_t + \bar{\tau}^k_t$. We also note that if intermediate good j is a fossil fuel and the sector pollutes only by burning fuel, then the marginal emission is a constant factor that converts fuel quantity into emissions.

The first-order condition for capital equates the user cost of capital to its marginal product df^n/dk. When the capital stock itself contributes to emissions, the user cost includes not only the standard cost of capital but also the marginal contribution to the tax bill. In contrast, if emissions arise solely from variable inputs such as fossil fuels, the first-order condition for capital is the same as without taxes. This is an implication of the linear rate schedule: in general, investment in a sector incurs a capital tax and also lowers the emission intensity for that sector. With a linear tax rate, these opposing effects exactly cancel, so the capital tax schedule does not distort the firm's investment decision. We revisit this issue when we discuss concave schedules in Section 5 below.

Other firms and government. Firms that make consumption, export and capital goods choose production plans to equate the marginal products of intermediates to intermediates' prices. To write their first-order conditions, we denote the nth partial derivative of a function g by g_n. We then have

$$
p_{t,n} = g_n\left(y_t\right) = \tilde{P}_t\tilde{g}_n\left(\tilde{y}_t\right) = p^k_{t,m}h^m_n\left(z^m_t\right),\ m \in \mathcal{N}. \tag{15}
$$

The first two equalities are FOCs for consumption and export goods producers, respectively. The last equality says that the marginal product of good n for a capital goods producer that sells

[6]When prices reflect marginal cost, and the tax term is the social cost of carbon, the equation is the same as the planner's first order condition (6).

capital to sector m firms at the price $p^k_{t,m}$ is also equal to the price of intermediate good n.

We assume that the government rebates all tax receipts lump sum to households. The government budget constraint is therefore

$$T_t = \sum_n \left(\tau^k_t \left(\varepsilon^n_t \right) v_{t,n} + \tau^c_t e^n \left(l^n_t, k^n_t, x^n_t, \tilde{x}^n_t \right) \right). \tag{16}$$

The transfer is equal to the sum of capital tax income and carbon tax income. We specify policy by a capital tax schedule τ^k_t, possibly nonlinear in emission intensity, and a carbon tax rate τ^c_t. The transfer T_t then adjusts so the budget constraint holds in equilibrium.

Competitive equilibrium. Equity market clearing requires that households' portfolio demand for equity of emission intensity ε is the same as the capital demand of all firms that choose production plans with emission intensity ε. Since we have a finite number of sectors, trade will occur only on a finite number of equity markets. Denoting by ε^n_{t+1} the emission intensity in sector n, we write market clearing in any market with positive trade as

$$s_{t+1} \left(\varepsilon \right) = \sum_{n \in \mathcal{N}: \ \varepsilon^n_{t+1} = \varepsilon} p^k_{t,n} k^n_{t+1}. \tag{17}$$

Here the right-hand side is the supply of equity by all sectors that choose emission intensity ε.

For a given capital tax schedule and carbon tax rate, an equilibrium consists of an allocation together with vectors of intermediate goods prices, capital prices, a wage, a government transfer and a return schedule such that (i) households maximize utility (1) subject to the budget constraints (7), (ii) intermediate goods firms maximize shareholder value (12), (iii) other firms optimize so first-order conditions (15) holds, (iv) households hold all equity of intermediate goods firms, (v) all domestic goods markets clear (2) (v) international trade is balanced (4), and the government budget constraint (16) holds.

We are now ready to state our equivalence result.

Proposition 1. *For any sequence of carbon tax rates τ^c_t, an equilibrium with carbon tax rate τ^c_t and no capital tax leads to the same allocation as an equilibrium with carbon tax rates $\hat{\tau}^c_t < \tau^c_t$ and a capital tax schedule*

$$\tau^k_t \left(\varepsilon \right) = \left(\tau^c_t - \hat{\tau}^c_t \right) \varepsilon. \tag{18}$$

In particular, if τ^c_t equals the social cost of carbon, then the equilibrium with capital tax schedule $\tau^k_t \left(\varepsilon \right) = \tau^c_t \varepsilon$ achieves the solution to the planner problem.

The proof follows from comparing equilibrium conditions under the two tax schemes. Only households and intermediate goods firms face different problems: households pay the capital tax, whereas intermediate goods firms pay the carbon tax. When the capital tax rate schedule is linear, decisions intermediate goods are determined by (14). In these conditions, the slope of the capital tax rate schedule enters exactly like the carbon tax rate, and if both taxes are present, the two parameters enter as a sum. All other firm first-order conditions are identical under the two tax schemes. The only other equilibrium condition affected by taxes is the government budget constraint (16). With a linear capital tax rate schedule $\tau_t^k(\varepsilon) = \bar{\tau}_t^k\,\varepsilon$, the firm values $v_{t,n}$ cancel out, and tax revenues on the right-hand side can be written as $\left(\bar{\tau}_t^k + \tau_t^c\right) e^n\left(l_t^n, k_t^n, x_t^n, \tilde{x}_t^n\right)$. The two tax parameters again enter only as a sum.

Proposition 1 compares the equilibrium effects of alternative tax schemes and hence the interaction of firms, households, and the government. To interpret the result, it is helpful to isolate the contribution of firms. The role of households and the government in the model is to provide a return schedule $R_{t+1}(\varepsilon)$ that incentivizes firms to save on emissions. The effects of this schedule on production do not depend on how exactly it comes about. More formally, we have

Proposition 2. *For any return schedule $R_t(\varepsilon) = R_t(0)\left(1 - \tau_t^c\,\varepsilon\right)^{-1}$, firms' optimization together with balanced trade as well as market clearing for intermediates and labor imply the same prices and production plans and hence emissions as under the carbon tax τ_t^c.*

Per our discussion above, the objective in intermediate goods firms' problem (12) reduces to (13) when the capital tax schedule is linear, so the slope $\bar{\tau}_t^k$ and the carbon tax rate τ_t^c enter as a sum. All other firm problems and the market-clearing conditions for intermediates and labor are unchanged.

The propositions underscore that incentives provided by a carbon tax and a capital tax schedule are perfect substitutes. Proposition 1 says that if we have a desired target carbon tax τ_t^c then, if an actual carbon tax $\hat{\tau}_t^c$ can be implemented, the slope of the capital tax schedule needed to get to the target should be $\tau_t^c - \hat{\tau}_t^c$. Proposition 2 provides an interpretation in terms of climate finance: if we have a desired carbon tax rate τ_t^c, but can impose only a carbon tax $\hat{\tau}_t^c$, then financial markets have to deliver a return schedule $R_t(\varepsilon) = R_t(0)\left(1 - \left(\tau_t^c - \hat{\tau}_t^c\right)\varepsilon\right)^{-1}$ in order to achieve the target carbon tax. The cross section of returns thus has to respond less to the emission intensity the higher is the actual carbon tax $\hat{\tau}_t^c$.

It is important that there is a capital tax rate *schedule*, and not a flat tax rate. The schedule ensures that capital owners and firms internalize the externality: capital owners are concerned about low after-tax returns, while firms worry about high costs of capital at high emission intensities. To understand what incentives the tax schedule has to provide, we thus not only want to know the tax bill paid *in equilibrium* with a given capital tax system, but also what off-equilibrium threats such a system must provide. It is natural to focus on two numbers per firm: the equilibrium tax rate on its value and the tax rate on its value if the firm did not adjust its emission intensity away from the initial equilibrium. Using a calibrated model, we can compute both numbers for every tax rate.

2.3 Discussion

In this section, we discuss the assumptions of our model and clarify that a number of features that our basic model abstracts from are not essential for the equivalence of incentives provided by the two tax schemes.

Objective of the firm and equilibrium concept. We have assumed so far that firms live for two periods: they raise funds to buy capital in the first period, then produce, and pay out the resulting capital income in the second period. This setup is a minimal way to talk directly about equity and have return premia depend on the emission intensity relative to market value. However, the Modigliani-Miller theorem holds in our model, so many equivalent alternative structures for the firm are possible. For an alternative example that helps to clarify the equilibrium concept, suppose firms live for only one period and rent capital that is owned by households. In this case, capital taxes are levied on households' capital holdings rather than their equity holdings.

Under this alternative market structure, households care about emission intensities when they rent out their capital, not when they invest. Instead of many equity markets indexed by emission intensities ε, we thus have many rental markets for capital. Since emission intensity is observable, rental rates vary accordingly, and household optimality determines a *schedule* of rental rates. Rental rates depend on emission intensity since households pass on capital taxes to firms by charging higher rates. This decentralization is familiar from models with variable capacity utilization, where depreciation, and hence the rental rate of capital, also depends on features of the production plan, namely utilization. Rental contracts for cars that depend on mileage also work this way.

The common denominator in both the rental and equity market decentralizations is that competitive markets can coordinate the sorting of resources by emission intensity—provided this information is publicly observable. In the rental market setting, the rent schedule provides price signals that guide tradeoffs between using capital with high emissions and higher tax payments. In the equity market setting, this job is performed by the return schedule. The market transactions that take place to implement coordination are of course different. In the rental market setting, we have within-period trades between firms and households. In the equity market setting, coordination involves firm decisions made by shareholders who acquire the firms. But the resulting allocation reflects the same optimal tradeoff.

Rents and other taxes. Our model assumes perfect competition in product markets and constant returns to scale, so firms do not earn any rents. We also focus solely on capital taxes and carbon taxes and do not allow for any other taxes, such as corporate income taxes. Neither assumption is essential for the equivalence result. Introducing decreasing returns, markups, or other taxes would modify the intermediate goods firm problem (12) only through the definition of the firm value (11). As a result, the key step in our derivation that makes the slope of a linear capital tax schedule enter like a carbon tax rate is unaffected.

Boundaries of the firm. Our decentralization assumes that every technology is operated by a separate firm. However, the equivalence result also extends to *multigood* firms, as long as emission intensity is defined as total emissions divided by total firm value. Intuitively, with frictionless financial markets, substitution of technologies across firms operating a single technology is the same as substitution by an individual firm across multiple technologies it operates. To illustrate this, we introduce multigood firm types $m \in \mathcal{M}$, where a firm of type m produces all intermediate goods $n \in \mathcal{N}^m$, a subset of the set of all goods. The multigood firms can coexist in any sector n with firms that operate only one technology.

A multigood firm of type m chooses a production plan $X = (X_n)_{n\in\mathcal{N}^m}$, which specifies inputs for each technology n the firm operates. The firm's date $t+1$ value for a given plan X is the sum of values contributed by the individual technologies. Each component is given by profits plus undepreciated capital, as in (11). The firm's overall value is thus

$$V_{t+1,m}(X) = \sum_{n\in\mathcal{N}^m} v_{t+1,n}(X_n)$$

The key new margin is that the firm at date t makes a portfolio choice over how to allocate capital across the technologies n it operates. Capital taxes are still assessed at the firm level and depend on the firm's emission intensity, defined as total emissions relative to firm value $V_{t+1,m}$.

A multigood firm chooses an equity market in which to raise equity, taking as given the return schedule, which depends on the firm's emission intensity ε. On the asset demand side, nothing changes, so the household Euler equations for equity (8)-(9) continue to hold. The multigood firm thus solves

$$\max_X \left\{ -\sum_{n\in\mathcal{N}^m} p^k_{t,n} k^n + R_{t+1}(\varepsilon)^{-1} V_{t+1,m}(X) \right\}, \qquad \varepsilon = \frac{\sum_{n\in\mathcal{N}^m} e^n(X_n)}{V_{t+1,m(X)}}. \tag{19}$$

This problem is directly analogous to the single-good firm problem (12). The only difference is that emissions are now a sum over emissions contributed by the different technologies n. The equivalence result thus follows by the same argument.

Risk. While our model so far is deterministic, the equivalence result extends to a setting with risk. What is important is only that financial markets are frictionless and shareholder value maximization is well defined. Suppose that households have standard expected utility preferences. We can allow for general exogenous shocks to technology: let ω_{t+1} denote the realization of shocks at date $t+1$. To make the point with minimal extra notation, we assume that shocks take on a finite number of values and that households assign some probability over sequences of states ω_{t+1} that reflects their beliefs. All expectations below are computed using this probability.

Introducing risk affects only households and intermediate goods firms that make intertemporal decisions. Within-period decisions by other firms work as before. For an intermediate goods firm, the production plan chosen at date t is now partly state-contingent because its variable inputs— labor l, intermediates x and foreign goods $\tilde{x}$—are all functions of the state ω_{t+1}. Capital remains a number k chosen at date t. We write the cum-dividend value of the firm at $t+1$ as $v_{t+1,n}(X;\omega_{t+1})$, where the last argument captures the direct effect of exogenous technology shocks on profit. These shocks could, for example, influence productivity in the firm's production function.

Since both input choices and firm value respond to shocks, emission intensity: ε is now a function of the state ω_{t+1}. When capital taxes are in place, the tax rate is therefore stochastic from the perspective of date t. The cross section of relevant equity markets is now indexed by *random variables* ε, not simply numbers. In the presence of taxes, an equity claim is different from another as long as it is taxed at a different rate with positive probability. Households and firms thus assess equity claims with different stochastic emission intensity profiles.

The household budget constraint (7) takes the same form as before, as long as variables are understood to be random variables. Likewise, the Euler equations (8)-(9) continue to hold. With a representative agent who prices all assets, the random marginal rate of substitution $R_{t+1}(0) = \beta u'(C_t) / u'(C_{t+1})$ serves as a stochastic discount rate for all contingent claims in the absence of capital taxation—it defines a random clean return. Returns on equity differ from this benchmark state by state, with deviations determined by the firm's emission intensity profile across states.

Shareholder value is now the *expected* present value

$$-p_{t,n}^k k^n + E_t\left[R_{t+1}(0)^{-1}\left(1-\tau_{t+1}^k(\varepsilon)\right)v_{t+1,n}(X;\omega_{t+1})\right]$$

where we have already used the Euler equation for the discount rate $R_{t+1}(\varepsilon)$. It is immediate that the problem with a linear capital tax schedule reduces again to a problem with a proportional carbon tax.

Scope 2 emissions. So far, we have focused exclusively on scope 1 emissions—that is, taxation of emissions generated directly through the use of intermediate goods—and we have assumed that electricity use is untaxed. In contrast, scope 2 emissions attribute emissions from electricity generation to the *users* of electricity, rather than the *producers*. It is possible to derive an alternative equivalence result with this convention. Suppose we redefine the emission intensity for non-electricity firms to include both scope 1 and scope 2 emissions, computed as the total of these emissions divided by the firm's enterprise value. We then introduce a linear capital tax rate as before. To avoid double-counting emissions, we set the emission intensity of electricity-producing firms to zero, thereby exempting them from capital taxation. We would then again obtain equivalence between capital taxation and carbon tax.

The distinction between capital taxes based on scope 1 versus scope 2 emissions is the same as taxing electricity at the producer or consumer level, respectively. As long as emissions are not double-counted, the two approaches lead to the same allocations. In a scope 1 approach, dirty electricity firms face higher costs of capital, leading them to charge higher electricity prices, which in turn discourage electricity use. In contrast, in a scope 2 approach, electricity prices are lower, but users are discouraged by capital taxes that take their dirty electricity use into account. A practical difference between the two approaches is that measurement of scope 2 emissions requires accurately attributing emissions to electricity use. An advantage of the scope 1 approach we have emphasized is that such an attribution is not necessary.

Scope 3 emissions, fossil fuel producers, and reserves. Scope 3 emissions encompass a wide range of additional measurement approaches, including dirtiness of inputs as well as how many emissions are generated during the use of a firm's product. For example, both petroleum producers and car manufacturers are attributed scope 3 emissions from gas-fueled cars. We are interested in equivalence to a carbon tax, which taxes every emission exactly once. As a result, the broad concept of scope 3 emissions discussed in policy debates is not suitable, and indeed not necessary. Our approach instead says that for asset returns to provide incentives like a carbon tax, it is sufficient to develop simple scores based on the intensity of scope 1 emissions.

A simple variant of our equivalence result incorporates a portion of scope 3 emissions by taxing the capital of fossil fuel producers. Suppose we eliminate taxes on fuel users and instead define the emission intensities of fossil fuel producers based on emissions generated by the downstream use of their fuels—emissions that are catergorized as scope 3 in emission accounting frameworks. We can then derive a set of replicating returns where only fossil fuel producers pay positive return premia, whereas all fuel users pay the clean rate. We note, however, that such a tax on its own covers only emissions due to domestically produced fuels, including those burnt abroad, and not imported fuels. An advantage of a capital tax based on scope 1 emissions is that it is easy to cover all domestic emissions, regardless of where fuels come from.

Capital taxes based on scope 1 emissions apply to fossil fuel producers only to the extent they themselves burn fuel, say, during extraction. Consequently, in our baseline specification, replicating returns on fossil fuel firms are relatively small. This contrasts with much of the existing literature on green investing, which emphasizes divestment from fossil fuels as a key strategy. We also note that our model can be readily extended to include exhaustible resources as assets in the spirit of Hotelling. In such an extention, fossil fuel reserves would from part of fossil fuel companies' value, and some of those assets could become stranded when a carbon tax is introduced. This effect does not change our results: similar to a carbon tax, the drop in the value of reserves would come from future low cash flows, rather than return differentials due to capital taxes.

Adjustment costs. Suppose adding new capital goods i_t^n to an existing capital stock k_t^n in sector n incurs adjustment costs $c^n\left(i_t^n/k_t^n\right)k_t^n$, measured in units of the final good. The function c^n is convex with a minimum at δ_n such that $c^n\left(\delta_n\right) = 0$. For simplicity, we take the function h^n in equation (2) to be the identity. To illustrate the resulting dynamics, we consider an infinitely lived intermediate goods firm and formulate its problem recursively, with capital as the only endogenous state variable. Due to constant returns to scale, the value function of the firm is linear in capital and can be expressed as $q_{t,n}k_t^n$, where $q_{t,n}$ is the shadow value of capital installed in sector n.

At date t, a firm comes in with capital stock k_t^n and chooses a production plan $X = (l, k, x, \tilde{x})$ for the next period. This plan matters for the equity market where the firm is traded at date t. The shareholders' required rate of return in that market determines the discount rate the firm uses to evaluate its production plans. As before, we define the firm's cum-dividend value at date $t+1$ as

$$v_{t+1,n}\left(X\right) = p_{t+1,n} f^{n}\left(l,k,x,\tilde{x}\right) - \sum_{j\in\mathcal{N}} p_{t+1,j} x_j - \tilde{p}_{t+1,j}\tilde{x}_j - w_{t+1} l + q_{t+1,n}\, k. \tag{20}$$

This expression has the same form as without adjustment costs, except it now includes the continuation value $q_{t+1,n}\, k$. The continuation value captures how future discount rates—which depend on future production plans—influence the present value. Because capital is the only endogenous state variable, only the marginal value of installed capital $q_{t+1,n}$ is needed to capture this effect.

We can now rewrite the shareholder value maximization problem at date t as

$$q_{t,n}\, k_t^n = \max_{i,X} \left\{ -p_{t,n}^k i - c^n\left(i/k_t^n\right) k_t^n - R_{t+1}\left(\varepsilon\right)^{-1} v_{t+1,n}\left(X\right) \right\},\ k = \left(1-\delta_n\right) k_t^n + i,\ \varepsilon = \frac{e^n\left(X\right)}{v_{t+1,n}(X)} \tag{21}$$

The new element in this problem is that the firm now faces adjustment costs in addition to the purchase cost of new capital. The capital stock k in the production plan X for next period consists of undepreciated old capital and new investment. We emphasize that this formulation makes no assumption on dividend policy. It does not matter whether the firm pays out profits and raises new money to finance investment, or retains earning to fund it.

Problem (21) demonstrates that the equivalence between carbon tax and capital taxes continues to hold in the presence of adjustment costs. The household side of the model remains unchanged, so the Euler equations $R_{t+1}\left(\varepsilon\right)^{-1} = R_{t+1}\left(0\right)^{-1}\left(1-\bar{\tau}_{t+1}^{k}\varepsilon\right)$ continue to hold. Substituting this expression into the firm's problem and using the definition of emission intensity again cancels the value $v_{t+1,n}$, just as in the baseline setting. The key difference to the baseline case is that the relevant intensity depends not only on the market price of capital (that is, the replacement cost), but also on the shadow value of installed capital to the firm. At the same time, the standard result still holds: the value of capital equals the market value of the firm.

Intuitively, adjustment costs do not alter the key mechanism underlying our equivalence result: emissions are generated when capital is used in combination with fossil fuels. A premium can then provide the same incentives as a carbon tax when it reflects the current use of fuel. It is not important that the funds raised might be used to purchase capital that may produce emissions in the future. All effects of future emissions on the value of the firm are already reflected in the shadow value of installed capital.

3 Replicating return premia without adjustment

In this section, we begin our quantitative study of the distribution of return premia that replicate a given carbon tax. From Proposition 2, the key input to this calculation is the distribution of emission intensities relative to capital. We proceed in two steps. In this section, we measure the *current* distribution of emission intensities and evaluate return schedules at those intensities.

The resulting return distributions can be used to interpret results on pollution premia from the empirical literature. If financial markets were currently providing incentives that replicate some carbon tax, then we should see premia of the magnitude predicted by the replication result.

The observed intensity distribution is relatively easy to measure: it requires only data on emissions and capital shares; it does not require a detailed calibration of the model. At the same time, current emission intensities cannot tell us what premia will be earned in equilibrium if a substantial carbon tax were in place. This is because introducing a carbon tax will incentivize firms' substitution away from fossil fuels. Current intensities would only be relevant if all technologies are Leontief, so intensities are constant. Assessing the equilibrium return schedule requires taking a stand on substitution elasticities. Our second step in Section 4 below calibrates the model and provides results on equilibrium adjustment.

A back-of-the-envelope calculation. To get an initial idea of orders of magnitude, we start from the emission intensity per dollar of gross output $\hat{\varepsilon}^i$, a commonly reported number in emissions accounts. The emissions are measured as CO_2e, or CO_2 equivalents, which express the global warming impact of different greenhouse gases relative to carbon dioxide. Across 2 digit NACE sectors in 2017, $\hat{\varepsilon}^i$ ranged between zero and about 14kg CO_2e per dollar, with the highest numbers for water transport, air travel, and electricity. To obtain emissions per unit of capital ε^i, we divide by the capital share in output, and multiply by the user cost of capital ρ_t^i :

$$\varepsilon^i = \hat{\varepsilon}^i \frac{p_{t,i} y_{t,i}}{\rho_t^i k_t^i} \rho_t^i. \tag{22}$$

In the absence of capital taxes, the user cost or rental rate ρ_t^i on capital is the interest rate plus the depreciation rate.

From Proposition 2, to replicate a carbon tax of \$10 per ton, we need $10\,\varepsilon^i$ extra return on sector i. We have $\hat{\varepsilon}_t^i$ ranging from zero to .012 tons per dollar. The capital share in gross output is roughly 39% . With an interest rate of 1% and a depreciation rate of 10%, ρ_t^i is equal to 11%. The dirtiest firms thus require an extra return of

$$10(0.01)\frac{1}{0.39}0.11 = 0.028.$$

In other words, to provide incentives equivalent to a \$10 higher carbon tax, the dirtiest firms have to worry that the spread can be 2.8% higher.

The example calculation shows that a modest carbon tax does not require large return differentials. However, since the required returns scale with the tax rate, sizable taxes like \$100 per ton call for substantial differentials. Moreover, moving from an intensity relative to output to an intensity relative to capital is not a simple rescaling that is the same for all sectors, say. Instead, for a given intensity relative to output, the translation depends on capital shares and user costs, both of which differ significantly across sectors. We now describe how we collect the relevant data and then present sector and firm-level results on replicating returns.

Sectoral data. We work with the GTAP 11 database from the Global Trade Analysis Project (Aguiar et al. 2023) to measure costs and emissions at the sector level. This dataset includes a social accounting matrix, that is, a record of annual transactions between country-sector pairs within a unified and consistent framework. The GTAP-Power module contains detail on the energy sector that goes beyond usual input-output matrices. In particular, the electricity sector is broken down by the type of fuel used to make electricity. We also observe physical quantities for transactions of electricity as well as other energy. The GTAP-E module contains numbers on scope 1 emissions due to fossil fuel use. The primary sources for the data are national account systems, customs statistics, and energy balances. The reference year is 2017. We focus on transactions within the U.S. as well as between the U.S. and the rest of the world, treated as an aggregate.

We consider a total of 72 sectors listed in Table 6 in Appendix A that correspond largely to NACE 2-digit definitions. There are 15 primary sectors, 27 in manufacturing, and 18 in services. We distinguish seven subsectors for electricity generation based on fuel: coal, gas, oil, wind, solar, nuclear, and "other". We also have 5 fossil-fuel sectors: coal, natural gas, crude oil, refined petroleum & coke, and gas manufacturing & distribution. We define two additional sectors that describe production within households. A *household vehicles* sector consists of the share of automobiles recorded as household consumption in GTAP plus household consumption of refined petroleum. To account for electric cars, we add the share of household electricity used for EVs[7] as part of the energy mix used to power household vehicles. A *housing* sector comprises GTAP's dwellings sector and all other household energy consumption. This approach ensures that household capital is grouped with the energy used to run it, as is the case for firms.

Our quantitative analysis focuses on emissions generated by burning fossil fuels to produce CO_2e. We back out sectoral emission intensities relative to capital following (22). For every sector, GTAP provides monetary values for gross output, materials and wages in 2017 dollars. Consistent with our model, we compute capital income for the sector as output less materials and wages. We assume that the user cost equals a common interest rate of 4% plus depreciation. To obtain sectoral depreciation rates, we merge GTAP to the *Fixed Asset Tables* of 2017 provided by the *Bureau of Economic Analysis*.

Sectoral results. Figure 1 presents sectoral distributions of capital and emissions together with replicating return premia by sector. Along the horizontal axis, we measure emission intensity in tons of CO_2e per million dollars. In both panels, every bar represents a sector or group of sectors. The height of the bars in the top panel reflects the sectors' share in the total capital of the economy, while the height in the bottom panel is the sectors' share in total emissions. In order to provide detail for high emission-intensity sectors, we group many low-intensity sectors into a supersector, "Rest," which is shown towards the left in the figure. To handle skewness, we also work with broken axes in the top panel.

The figure makes two key points that are central to all our quantitative results. First, **the**

[7] U.S. Energy Information Administration, *Electric Power Monthly*, December 2023, Table D.1. We use the first available data point, for 2018.

distribution of emission intensities is extremely right-skewed. Only a handful of sectors that account for a small share of total capital sit at emission intensities above 100 tn/$M. They consist of refining, oil-fueled transport sectors (navigation, aviation, and land transport), coal- and gas-fueled electricity generation, and a few dirty manufacturing sectors, in particular chemicals. Together these sectors also account for a large share of total emissions. We note that households also contribute significantly to total emissions, especially through vehicle use. The majority of capital, in contrast, is held by relatively clean sectors, such as the large service sectors, which produce few emissions.

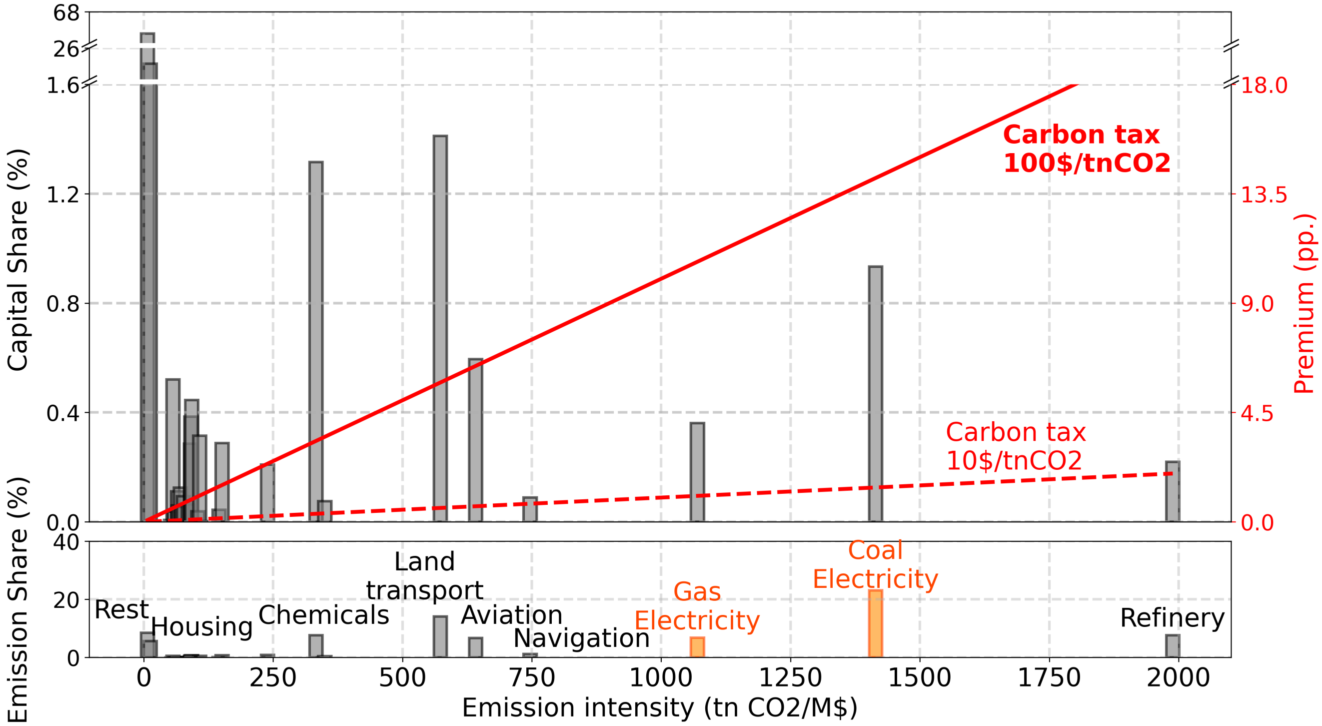
The second fact is that the **replicating return premium is small for most sectors but very large for a small number of really dirty sectors**. We plot two lines to indicate premia that replicate carbon taxes of 10 and 100 dollars per ton of CO_2e, respectively. It follows from (10) that replicating premia are (approximately) linear in intensity. For the serious $100 carbon tax, most capital should command a small premium of only a few basis points. The premium for chemicals is 3.5%, close to the upper bound of estimates on pollution premia in the literature. For the even dirtier transport and power sectors, premia are even larger, topping out at 17% for the .2% of total capital that is invested in refineries. For dirty electricity subsectors using gas and coal, premia are 4% and 11%, respectively. Of course, the dirtiest sectors are served by multi-sector firms, which motivates a closer look at the firm level.

Firm- and division-level data for electricity generation. S&P Global Trucost provides firm-level information on electricity production and emissions by type of fuel for publicly traded power companies. We consider active U.S. companies with positive electricity generation in 2017 and merge data on those firms to Compustat Fundamentals to add a firm-level measure of enterprise value, that is, the combined value of debt plus equity. Enterprise value is a model-consistent measure of total capital. At the firm level, we thus have a direct measure of the emission intensity relative to capital for 45 firms. In 2017, the 45 firms in our data produced 47% of the electricity in the U.S. as recorded by GTAP. Their enterprise value accounted for 44% of the capital we back out at the sectoral level.

We are also interested in heterogeneity of power plants that use the same fuel. We define a *division* as the collection of all plants of the same firm that use the same fuel. Unfortunately, we do not have plant-level data on the value of capital. As a rough estimate, we divide the enterprise value of the firm among its divisions in proportion to the quantity of electricity produced. We obtain a sample of 203 divisions, with 111 clean divisions that do not produce any emissions and 92 dirty divisions. Only 3 firms contain only one division—the typical case is thus for one company to rely on multiple fuel types. In particular, 99% of total capital is held by firms that own both clean and dirty (gas, oil or coal) plants. Those "mixed" firms own 99% of the total clean capital and virtually all of the dirty capital.

Firm- and division-level results Figure 2 presents the distribution of capital and replicating return premia for the electricity sector at the firm level (bottom panel) and division level (top panel). The heights of the bars indicate shares of total electricity sector capital. Most of the capital is employed in clean divisions: the leftmost bar at zero represents 43% of total electricity

Figure 1: Replicating return premia by sector, no input adjustment

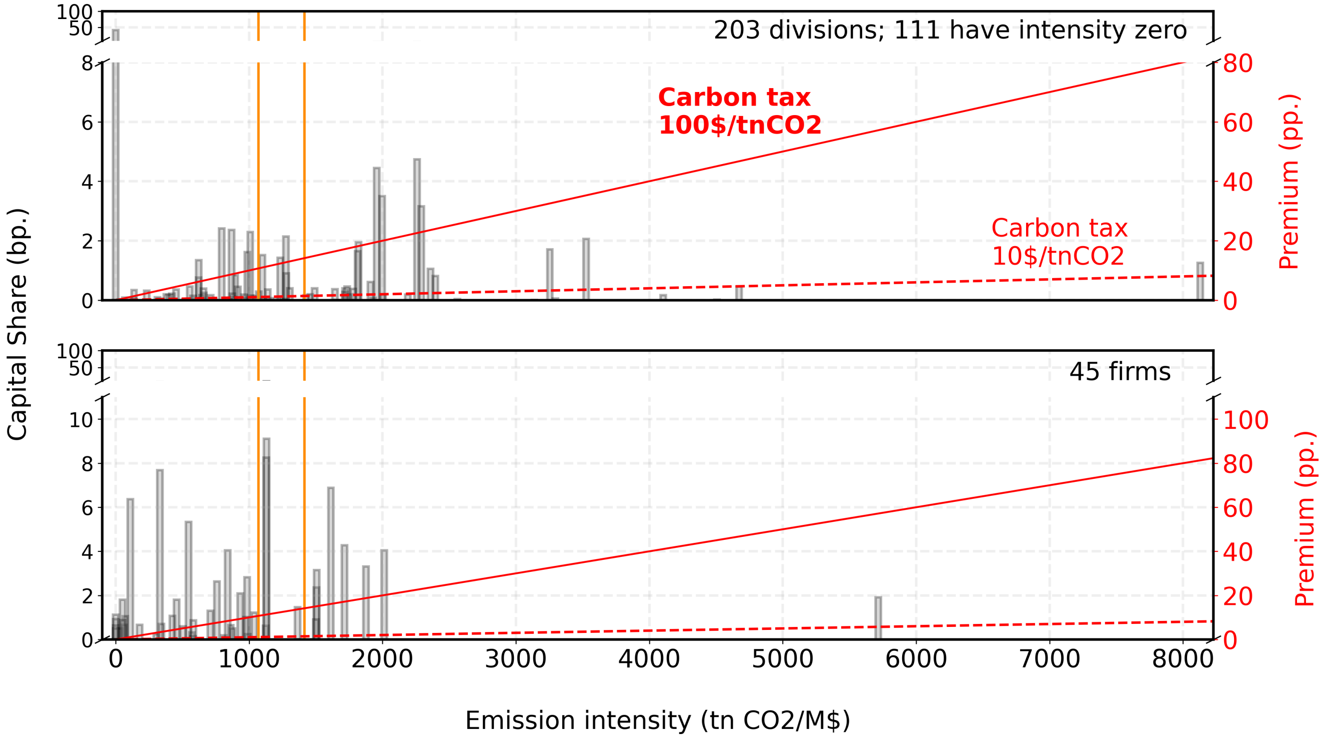


Note: The upper figure shows the capital share, the emission intensity ε^i, and the replicating premium of each sector. Each sector is represented by a bar, except for sectors with little intensity (Rest). The red solid line describes the premium schedule that replicates a \$100 carbon tax, while the dashed line describes the schedule that replicates a \$10 carbon tax. The lower figure measures the emission share of each sector along the left axis.

capital. We mark by yellow vertical lines the sectoral averages for gas- and coal-fueled electricity from GTAP already recorded in Figure 1. Finally, we add two lines that allow us to read off annual replicating returns for carbon taxes of \$10 and \$100 per ton of CO_2e. We note that the range of the horizontal axis is much larger than at the sectoral level in Figure 1 since the dirtiest electricity firm produces more than four times as many emissions per unit of capital than the dirtiest sector.

We take away two main points from these more granular numbers. First, **within-sector heterogeneity in emission intensities and hence replicating return premia is substantial**. To illustrate, the division-level coefficients of variation in the emission intensity are 79% among gas-powered divisions and 72% among coal-powered divisions. If the dirtiest divisions were stand-alone firms, the replicating premia would thus have to be extremely large. Second, **co-ownership of clean and dirty plants compresses the (equally-weighted) distribution of replicating premia.** The firm-level histogram in the bottom panel shows hardly any capital at zero. While the capital-weighted premia distributions are equal by construction, the equally-weighted distribution of premia has a mean of 9% and an inter-quartile range of 7 pp among firms with positive emissions. In contrast, among divisions with positive emissions, the mean of equally-weighted premia is higher at 14%, and the inter-quartile range is wider at 12 pp.

Figure 2: Replicating return premia in electricity sector, no input adjustment



Note: The plot shows the capital share, the emission intensity ε^i, and the replicating premium for each division (upper plot) and each firm (lower plot) within electricity producers. Each division or firm is represented by a bar, except for the bar at zero intensity, which bundles many firms or divisions. For reference, we added in yellow lines, which are sector-level references for gas-powered electricity and coal-powered electricity. The red solid line describes the premium schedule that replicates a \$100 carbon tax, while the dashed line describes the schedule that replicates a \$10 carbon tax.

4 Equilibrium replicating returns

We now compute equilibria of our model and determine equilibrium replicating returns for alternative carbon tax rates. This step requires taking a stand on more details of the production function, in particular elasticities of substitution between inputs.

4.1 Calibration and equilibrium adjustment

We assume that the production functions $g, \tilde{g}, h^n$ and f^n are nested CES functions. Each nest is parametrized by an elasticity of substitution and a set of nest weights that sum to one. Our choices for nests and many elasticities follow the MIT U.S. regional energy policy (USREP) model described in Yuan et al. (2019), another multisector model with extra energy detail. We present details in Appendix D, where we also show that our results are broadly similar to the EMF 32 study on carbon tax scenarios (McFarland et al. 2018), a meta-study performed by the Energy Modeling Forum with several leading models for U.S. environmental policy analysis. Here we provide a sketch that highlights key properties that drive the results.

Overview of energy use & emissions. To illustrate how energy use and substitution potential vary across the economy, we group sectors into six broad supersectors. Table 1 presents each supersector's shares of capital and emissions—as in Figure 1—alongside their share of output, energy use, and energy expenditure as a proportion of total revenue. Two of these supersectors are energy producers. The *fossil* sector handles the extraction of primary energy sources, crude oil, natural gas, and coal, refines oil into secondary energy sources such as gasoline, and distributes gas to users. The electricity sector generates and distributes electricity. All forms of energy are measured in a common unit.

Table 1: Supersector overview

	Shares of aggregate (%)						Revenue shares (%)	
Supersector	Emissions	Capital	Coal	Oil	Gas	Electricity	Energy	Electricity
Fossil	9.1	2.3	4.5	52.2	19.0	3.2	49.3	1.9
Electricity	30.3	2.6	91.4	0.5	26.8	5.4	22.8	5.4
Transport	22.0	2.1	0.0	23.3	2.9	1.5	16.7	0.7
Dirty man.	9.5	2.1	2.2	5.3	13.9	6.3	7.5	2.7
Households	18.5	25.3	0.0	14.1	17.8	33.6	11.5	6.5
Other	10.7	65.7	1.8	4.5	19.6	50.0	1.0	0.8

Note: Summary of energy by user and producer. Shares of aggregate report the share of each supersector to the aggregate variable in each column. Share of sector revenue report input bills as a share of revenue of energy and electricity for each supersector.

At this broad level of aggregation, the pattern of pollution in the U.S. economy is relatively simple. Energy producers generate emissions by burning coal to generate electricity and by refining oil. Oil products are burned by households and firms for transportation. Gas is used throughout the economy, most intensively in electricity and "dirty manufacturing", defined as manufacturing sectors with high emission intensities, notably chemicals, iron and steel, non-ferrous metals, and other mineral products. Both households and the "other" supersector, which comprises mostly service-sector firms, use substantial amounts of gas for heating and also account for almost all electricity use. Energy expenditures represent only a small share of total revenue outside the energy sector itself.

Production functions in a typical energy-using sector allow only limited substitution between variable inputs. In particular, there is little scope for electrifying transport or manufacturing. As a result, energy users primarily adjust by reducing their overall energy consumption. The electricity sector is an exception: it features competition between varieties produced with very different emission intensities. Aggregation of varieties takes into account the cost of the power grid, constraints on hydro and nuclear power, and the intermittency of renewables, but allows for substantial "cleaning" of electricity production. Standard trade elasticities enable relatively easy substitution between domestic and imported goods. Finally, because energy represents a small share of total revenue, energy-price changes have only a minor effect on output in most sectors.

Equilibrium allocations. We conduct comparative statics across steady states that differ only in the level of the carbon tax. The top panel of Table 2 reports aggregate statistics for carbon taxes of \$10, \$50 and \$100 per ton. In our benchmark case of a \$100 carbon tax, emissions fall by nearly 50%, accompanied by a modest 1.5% decline in output. We break down this emission reduction into three components: percentage changes in capital K, energy intensity (final energy use F relative to capital), and emissions E per unit of final energy.[8] The aggregate economy lowers emissions through a slight contraction combined with substantial energy savings—a 12% drop in the aggregate emission intensity—and most importantly a shift towards cleaner energy. Aggregate electricity declines by 9%.

Table 2: Aggregate effects under different carbon taxes

Panel A: Aggregate effects under different carbon taxes

	Percent Changes				Components of Emission Reduction		
Carbon Tax (\$)	ΔC	ΔY	Electricity	E	ΔK	$\Delta F/K$	$\Delta E/F$
10	−0.1	−0.2	−1.8	−9.6	−0.4	−3.4	−6.0
50	−0.7	−1.1	−6.4	−33.3	−1.7	−10.0	−24.6
100	−1.4	−2.0	−8.8	−48.4	−2.7	−12.5	−39.3

Panel B: Decomposition by supersectors at \$100 carbon tax

		Emissions		Components			Output
Supersector	Share	ΔE/total E	$\Delta E/E$	ΔK	$\Delta F/K$	$\Delta E/F$	ΔY
Fossil	9.1	−5.1	−55.9	−29.7	12.3	−44.2	−32.9
Electricity	30.3	−26.2	−86.3	38.1	−20.3	−87.6	−8.8
Transport	22.0	−5.0	−22.6	−4.7	−18.7	−0.1	−8.2
Dirty manuf.	9.5	−3.1	−32.3	−5.0	−26.0	−3.7	−7.4
Households	18.5	−5.5	−29.6	−2.8	−22.3	−6.8	−6.9
Other	10.7	−3.6	−33.8	−3.3	−19.4	−15.1	−1.6

Note: Panel A reports effects of carbon taxes on macroeconomic variables and decomposition of emission reductions in changes in capital, changes in energy intensity and changes in emission intensity as percentage point contribution of overall emission reduction. Panel B decomposes the emission reduction by supersectors. The first part report emissions reduction as a share of total economy emissions and as a share of own emission. The second part reports changes in capital, changes in fuel use per capital and changes in emissions per fuel use. The third part shows output reduction in each supersector.

The bottom panel of Table 2 shows how different sectors contribute to the overall emission reduction. The electricity sector alone accounts for roughly half of the total decline. It achieves this mostly by substituting towards cleaner fuel, rather than saving energy or shrinking—

[8]We report percentage changes rather than log changes, so there is a residual not shown in the decomposition. This residual can be significant when changes are large. Final energy represents all energy used, including from secondary sources such as gasoline or electricity.

in fact, its capital stock grows substantially. In contrast, the fossil sector contracts sharply. Non-energy sectors maintain roughly the same scale but lower emissions mainly by reducing energy consumption. The "other" and household sectors partially substitute gas with electricity. However, households and the transport sector continue to rely on oil and thus substitute little.

Smaller carbon taxes lead to correspondingly smaller reductions in emissions and economic activity. When we lower the tax rate from \$100 to \$50 (or \$10), the resulting losses in consumption and output scale roughly in proportion—declining by about one-half (or one-tenth). Emissions, however, fall less proportionately, decreasing by only one-third (or one-fifth). This nonlinearity reflects the skewed distribution of emissions and emission intensities across sectors, which makes the marginal emission benefit of targeting the dirtiest sectors disproportionately larger than that of other sectors. Moreover, the decomposition of emission-intensity changes reveals that energy savings (a lower energy intensity relative to capital) contributed more prominently to emission reductions at lower intensities, whereas fuel substitution becomes more important at higher intensities.

Our model includes no adjustment costs beyond a one-period time-to-build constraint. Along a transition path, gradual adjustment would therefore only come from consumption smoothing. Since aggregate capital moves little even in response to a large carbon tax, the transition is likely to be fast. From a macro perspective, the introduction of the tax is more like a short recession than a structural change requiring a long adjustment period. The adjustment that generates the large reduction in emissions is sectoral reallocation, particularly through the substitution of variable inputs such as primary energy. This helps explain why even models with richer adjustment costs, as featured in the EMF 32 study, tend to exhibit relatively fast transitions, with most environmental gains realized after a few years (see Appendix D for references and further details). We thus interpret our steady state comparison not as characterizing long-run outcomes, but rather as capturing the economy's response over a 5-10 year horizon.

4.2 Equilibrium returns

Equilibrium replicating returns are significantly smaller than replicating returns without endogenous adjustment of emission intensities. This is because the carbon tax provides strong incentives for substitution away from dirty fuels. Table 3 presents equilibrium replicating returns for a \$100 carbon tax and compares them to returns without adjustment. The leftward shift of the distribution is readily apparent. In particular, the basis point reduction in return premia is larger for dirty firms in the upper tail. These firms adjust relatively more: for example, the median premium drops from 6bp to 4bp, whereas the 95th percentile drops from 333bp to 61bp. The bottom two lines in the table display premia for the electricity sector. Here the difference in premia is extremely strong with premia declining in the right tail by more than 10pp.

To get intuition for what sectors see larger differences between equilibrium returns and those without adjustment, consider the example of a sector with a CES production function with equal weight on only two inputs, capital and some fossil fuel j that trades at the price p_j, say. The

Table 3: Premia with and without equilibrium adjustment

Quantiles	50th	75th	90th	95th	99th
No Adjustment, Sectors	6	13	45	333	642
Equilibrium, Sectors	4	7	36	61	465
No Adjustment, Electricity Firms	975	1501	1613	1876	2013
Equilibrium, Electricity Firms	21	74	109	165	368

Note: Premia in basis points. All premia calculated from a $100 tax per ton of CO_2e.

premium for a firm producing at intensity ε is $\tau_c\,\varepsilon$. Differentiating the first-order condition of such a firm, a small increase in the carbon tax leads to a change in its return premium by a factor

$$\frac{d(R_t(\varepsilon) - R_t(0))}{d\tau^c} = \varepsilon\left(1 - \sigma\frac{\tau^c\phi_j}{p_j + \tau^c\phi_j}\right). \tag{23}$$

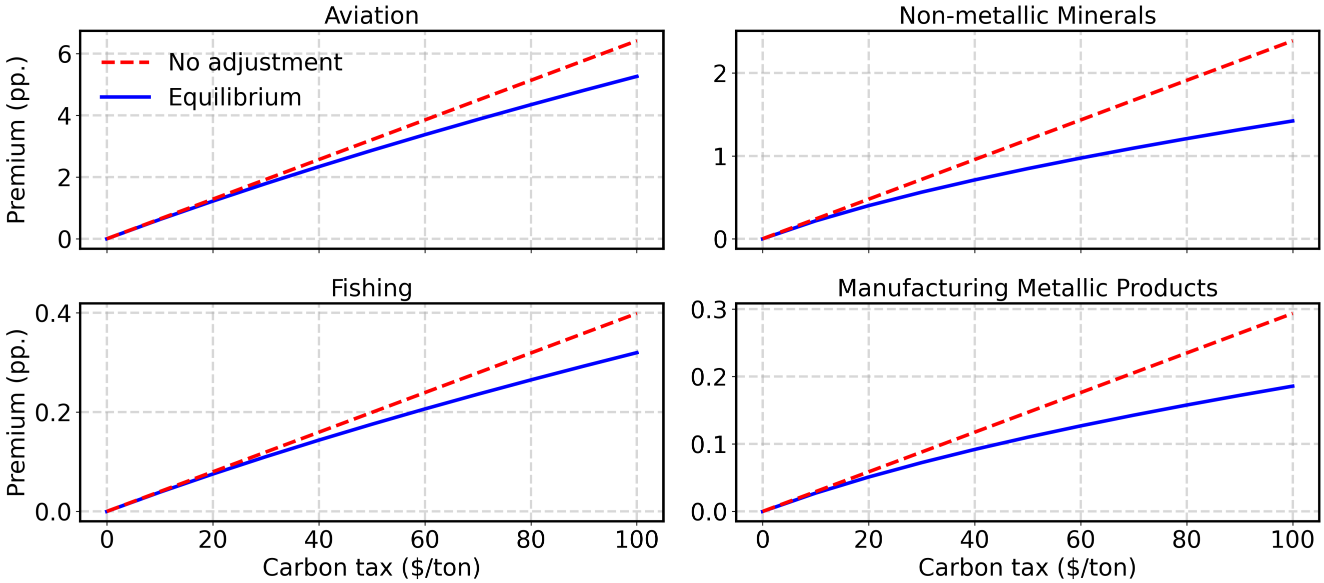
A direct effect increases the spread by ε. In addition, equilibrium adjustment lowers the equilibrium intensity, adding a second, negative, effect.

The size of equilibrium adjustment increases with two features of technology. The first is substitutability of inputs: higher σ means that when fuel becomes more expensive, firms substitute more easily towards cheaper inputs and thereby lower their emission intensity more. As a result, the extra spread required to replicate a higher carbon tax is smaller. The second feature is the share of carbon taxes in total fuel cost. If the carbon tax represents a larger share of the total fuel cost, then a change in the tax rate translates into a larger percentage change in the fuel cost and, hence, a larger reduction in intensity. Holding fixed the production function, a firm using dirtier fuel with a lower spot price thus pays a lower replicating spread in equilibrium.

Figures 3 and 4 illustrate the shape the cross section of replicating premia for firms that use many more inputs than the simple firm characterized by (23) and that are faced with larger changes in the carbon tax. Figure 3 considers several non-energy sectors, while Figure 4 looks at electricity. In each panel, the solid blue line shows the sector-specific premium as a function of the carbon tax rate, measured along the horizontal axis. The slope and hence the shape of the curve can be understood from (23). At zero initial tax, a small tax increase has a negligible effect on the fuel cost, so the response is the same as without any adjustment ($\sigma = 0$). The slope of the curve at zero therefore isolates the direct effect, which is linear in the tax rate, and drawn as a dashed red line. At low taxes, a linear approximation is fairly accurate. At higher taxes, however, adjustment begins to matter, and the blue curve diverges from the red line.

The figures clarify the importance of fuel cost for adjustment. In particular, coal is a fuel with an emission factor that is high relative to its spot price. In other words, burning coal is a cheap way to produce emissions compared to burning natural gas, and in particular compared to burning oil. As a result, coal-using sectors exhibit a particularly large equilibrium adjustment in returns. To replicate a $100 per ton carbon tax on coal-based electricity, for example, requires an 11% premium without adjustment, but less than 5% in equilibrium. This reduction is much

Figure 3: Replicating return premia as a function of the carbon tax rate



Note: Replicating premia in percent per year for different carbon tax rates (horizontal axis) and selected sectors. Dashed red lines show premia without adjustment, solid blue lines premia at equilibrium intensities.

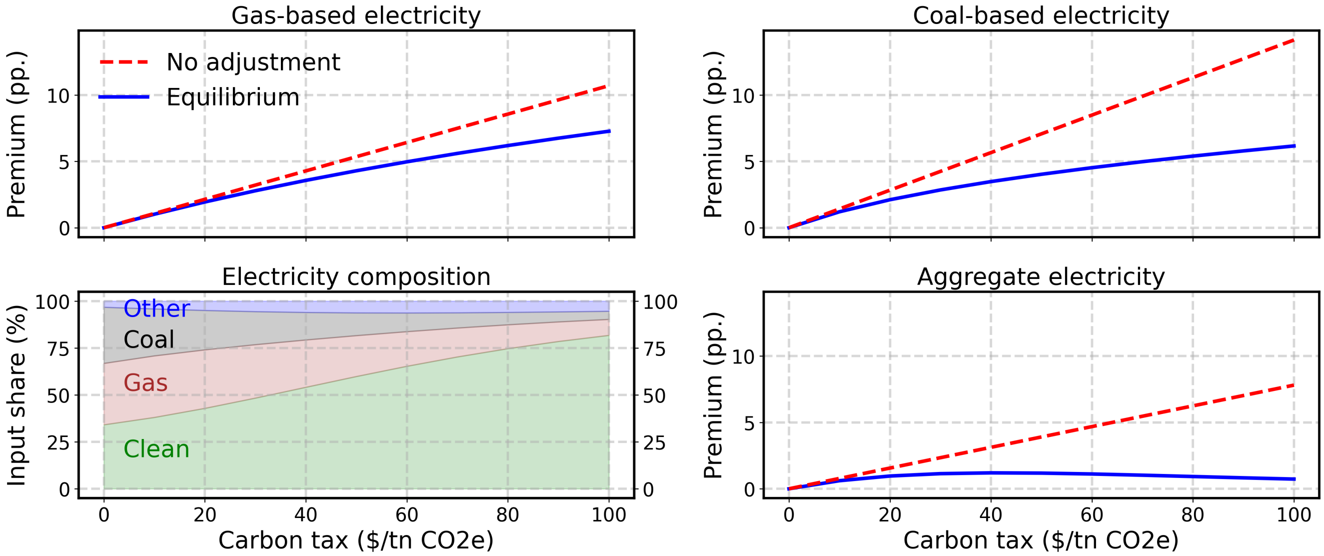
larger than for gas-fueled electricity, which has similar substitution elasticities between fuel and other inputs. At the same time, oil-using sectors such as aviation and fishing in Figure 3 show minimal adjustment, and equilibrium premia resemble those without adjustment.

The bottom left panel of Figure 4 summarizes substitution of the electricity sector across fuel types. As expected in models such as ours, a lot of substitution is possible by reducing dirty power generation and increasing instead clean power, in particular wind and solar. The bottom right panel shows replicating premia for the aggregates electricity sector. They capture both the adjustment at the fuel-type level and the shift to clean fuels. Overall, we obtain a very large adjustment effect: even high carbon taxes require only small replicating premia. In fact, the equilibrium premium schedule is decreasing beyond a carbon tax of about $50 per ton. Intuitively, when the potential for substitution is high, endogenous cleaning of the electricity sector can generate lower equilibrium premia.

Table 4 shows how different margins of adjustment in the electricity sector contribute to the overall reduction in emissions, or the case of a $100 carbon tax. For each fuel type, we decompose the overall change in emissions into three components. We first ask how much emissions would change from only capital reallocation across firms, holding fixed firms' capital allocation to different technologies as well as their emission intensities. This component is positive for all fuel types, that is, initially dirtier firms end up with more capital as a result of the carbon tax. The numbers are also small, indicating that reallocation of capital across firms of different average intensity is not an important effect.

The second component is reallocation of capital across divisions within a firm. This is

Figure 4: Replicating return premia as a function of the carbon tax rate



Note: Replicating premia and composition of production in electricity sector. Top line shows replicating premia in percent per year as a function of the carbon tax rate for gas- and coal-powered electricity sectors, bottom right panel for aggregate electricity sector. Dashed red lines show premia without adjustment, solid blue lines premia at equilibrium intensities. Bottom left panel shows shares of total electricity output contributed by subsectors as a function of the carbon tax rate.

clearly where the key emission reductions come from: firms substitute away from coal and gas by shutting down dirty plants, shrinking those divisions and ramping up investment in renewables. By construction, growth in renewables here reflects wind and solar power, as we have constrained the capital stock of nuclear and hydro power. An experiment that lifts these constraints implies a large shift into nuclear and hydro instead, resulting in slightly lower electricity prices, but otherwise relatively similar results. The final component is the change in intensity, which contributes little, as one would expect for subsectors that specialize in particular fuels.

Table 4: Sectoral Contributions to Emissions Changes

Electricity Type	**Firm capital**	**Division Share**	**Intensity**	**Total**	**Emission share (baseline)**
Coal	7	-72	-5	-70	76
Gas	9	-25	-2	-18	22
Other	1	0	0	1	2
Total	17	-97	-7	-86	100

4.3 The role of technology, trade and taxes on households

In Table 5 , we present results on aggregates and equilibrium under a number of alternative scenarios to highlight the role of some of our assumptions.

Electricity. Since substitution within and towards electricity is a key force in emission reduction, Table 5 reports results for alternative electricity production functions. First, we make it easier for energy users to substitute electricity for other fuels. The *high electrificiaton elasticity* scenario raises the substitution elasticity to one, more than double the baseline value of 0.4. Electricity production declines by less than in the baseline and emissions decline by an extra 3pp, indicating a relatively modest sensitivity to this parameter. Second, the *low intermittent electricity* scenario reduces the elasticity of substitution between intermittent (wind and solar) and baseload electricity to zero. As cleaning of electricity becomes more expensive, electricity falls by more and emissions increase by 10pp less than in the baseline. The contribution of the electricity sector to emissions reduction is halved, although the overall reduction still amounts to a substantial 38pp.

Table 5: Scenario Analysis Results

Scenario	Output (%)	Emissions (%)	Premia (bp) p50	p95	Elec. firms (bp) p50	p95	Extra Metrics
Carbon Tax 100	-2.0	-48.4	4	70	21	165	Imported Carbon 4% Electricity -9% Nuclear Energy 0% Solar Energy 684%
No HH taxed	-1.3	-43.1	4	70	22	165	-
Only Elec. taxed	-2.0	-48.4	-	-	21	165	Electricity -9%
High Trade Elasticity	-1.5	-52.7	4	70	21	165	Imported Carbon 5%
Low Trade Elasticity	-2.1	-47.4	4	70	21	165	Imported Carbon 4%
Low Intermittent Elasticity	-2.3	-38.9	4	143	334	596	Electricity -13%
High Electrification Elasticity	-2.0	-51.1	3	72	22	200	Electricity -4%
Flexible Nuclear	-2.1	-50.4	4	57	19	73	Nuclear Energy 280%
Solar Innovation	-0.3	-52.2	3	56	0	0	Solar Energy 6997%

Note: Output and emissions changes are in percentage change relative to no carbon tax. Premium values are in basis points (bp.). p50 and p95 refer to the 50th and 95th percentiles of the premium distribution respectively. Imported carbon are total emissions generated in foreign countries from the production of U.S. imports, relative to domestic emissions without carbon tax. Electricity is the percentage change in electricity consumption, relative to no carbon tax. Nuclear and solar energy is the percentage change in nuclear energy consumption, relative to no carbon tax.

Technical progress in electricity. We also explore two scenarios for technical progress that lowers the cost of expanding clean electricity. The *Flexible nuclear* scenario removes a constraint on the capital stocks of nuclear power that we maintain in the baseline, along with a constraint on hydro, motivated by the recent stagnation in these technologies. If nuclear power is instead unconstrained, it emerges as a competitive clean energy source, leading to a 3pp extra reduction in emissions. Nuclear generation increases substantially, partially replacing wind and solar, which play a larger role in the baseline case. The second scenario assumes a technological improvement in solar power, modeled as a 10% increase in solar TFP. This results in a 5pp additional reduction in emissions, highlighting the potential of continued innovation in renewables to support decarbonization.

While all specifications in Table 5 study the same $100 carbon tax, alternative assumptions on technology matter for equilibrium replicating returns. Interestingly, higher emissions need not go along with higher premia in the right tail. For example, high electrification makes dirty electricity more profitable, so more dirty capital is retained and premia in the right tail are higher than in the baseline, although emissions overall are lower. Substitution to cleaner power shows up as a 1bp reduction in premia at the median, a small reduction spread over many firms. In contrast, when clean electricity is more expensive because of its intermittency, then dirty electricity firms produce more and their premia rise along with emissions. Similarly, when technical progress crowds out dirty electricity firms, the right tail of premia flattens out.

International trade. Since our exercise introduces a carbon tax in the U.S. only, while holding the prices of foreign goods fixed, it makes sense to import "dirty goods" that are now more expensive to produce domestically. To roughly assess the resulting "leakage" of emissions, we define a notion of "imported carbon" that can be computed with the data we have: we sum up all extra imports after the tax is imposed and compute emissions that would have occurred if those goods had been produced in the U.S. at the old pretax emission intensities. For the baseline exercise, imported carbon amounts to 3.9% of pretax emissions. When we increase the Armington trade elasticity to 8 from its baseline value of 2.5 in the *High trade elasticity* scenario, domestic emissions decline by 4pp via substitution to foreign goods, while imported carbon increases by 1pp. We take away that leakage is present but relatively small. Moreover, it does not affect replicating returns, which do not change across scenarios.

Selective taxes. A final set of robustness checks removes carbon taxes on select sectors. When we remove the tax on households, the emission reduction declines by about 5pp. When we remove taxes on all sectors but electricity, we retain an emission reduction of 25pp. In both cases, the numbers are close to the sectors' contribution to the baseline result. Moreover, replicating returns change little. We conclude that decompositions of the effects into households, industry, and power sector are close to linear, and not subject to strong interaction effects. These results show that if a capital tax or otherwise generated return schedule can reach only firms, and not households, it nevertheless generates substantial emission reductions. Moreover, a tax that focuses on electricity can reduce emissions without large spillovers on other sectors – we return to this point when we turn to heterogeneous agent economies where some agents obtain nonpecuniary benefits from owning electricity capital.

5 Investor taste for clean assets

We now ask how a schedule of capital taxes can emerge not through regulation but as the result of household preferences for clean investment. We distinguish between two types of preferences. Agents with *nonpecuniary cost* experience discomfort when their portfolio contains equity in dirty companies. In contrast, agents with *nonpecuniary benefit* experience pride from holding particularly clean portfolios. We further allow for *sector-specific preferences*, where agents may derive utility from holding clean assets in specific sectors, such as clean electricity firms. As a result, equity markets in this section distinguish firms not only by their emission intensity, but also by sector. A portfolio is thus represented as a collection of nonnegative equity (or capital) holdings, with $k_{t,n}(\varepsilon)$ denoting the equity held at time t in firms in sector n that produce with intensity ε.

5.1 Extending the model

Our main interest is in the effects of cross-sectional heterogeneity in investor preferences on aggregate emissions. To isolate this mechanism, we shut down any dynamics of the wealth distribution that would result from differential portfolio performance. Specifically, we adopt the common modeling device of a large family that pools resources. We now describe the optimization problem of the family, which delivers asset pricing conditions and portfolio allocations for family members with different tastes for clean investment. The supply side of the model remains the same as in the economy with capital taxes above, so the definition of equilibrium changes only minimally. For simplicity, we assume throughout this section that all capital goods have the same price as the final consumption good.

Household sector: a large family of investors. More formally, a continuum of households of mass one constitutes a large family. Individual member households differ in their concern for the environment. A share κ^g of *green* households dislike capital more when it is used to generate more emissions. The felicity of a green household who consumes c_t^g and holds a portfolio with $s_{t,n}^g(\varepsilon)$—the amount invested in equity of firms in sector n with emission intensity ε—is given by

$$u\left(c_t^g - \gamma \sum_n \int (\varepsilon - \varepsilon_n^*)\, R_{t,n}(\varepsilon)\, s_{t,n}^g(\varepsilon)\, d\varepsilon\right), \tag{24}$$

where the scalar $\gamma > 0$ governs the strength of the green investment motive, and ε_n^* is a threshold that regulates whether green taste for firms in sector n is positive or negative.

If the threshold is zero, $\varepsilon_n^* = 0$, for all sectors, then any emissions generate *nonpecuniary costs*, or disutility, for green investors. We have set up preferences such that this cost is proportional to the *payoff* from a position, that is, return times investment, rather than simply the amount invested, $s_{t,n}^g$. In other words, disutility arises when consumption resources at date t are derived from income generated by dirty production at t. We view this timing convention as both plausible and convenient, though it is not essential for our results. What matters is that there is some nonpecuniary effect of investment on utility. Our functional form further treats consumption and the nonpecuniary benefits of green investing as *perfect substitutes*, which rules out wealth effects and isolates the role of taste heterogeneity.

A positive threshold $\varepsilon_n^* > 0$ in some sector n implies that investors derive positive *nonpecuniary benefits* from holding firms with emission intensities $\varepsilon < \varepsilon_n^*$—that is, firms that are cleaner than a sector-specific benchmark. In principle, the threshold could be the same for all sectors.

With equal ε_n^*s, green investors would perceive the same benefits from any clean capital. Such an economy-wide threshold would function similarly to a broad subsidy for all clean capital. We do not pursue this case. Instead, we focus on specifications where $\varepsilon_n^* > 0$ for only a few sectors n. This specification reflects investors' ambition to "clean up" particularly dirty sectors, such as electricity in our quantitative example below. With sector-specific preferences, a green investor may prefer a relatively clean (but still dirty) firm within their favored sector n to a cleaner firm in another sector. We assume that there are always some sectors n such that $\varepsilon_n^* = 0$.

The remaining share of households, $\kappa^t = 1 - \kappa^g$, are *traditional* households who derive utility solely from consumption, with felicity $u\left(c_t^t\right)$. The family pools resources and chooses the aggregate capital allocation s_t, but individual members are responsible for investing the same per capita amount of that total. Specifically, each member must invest an amount $\kappa^i s_t$, where i indexes green and traditional taste. Formally, equity holdings for each type must satisfy:

$$\kappa^i \sum_n \int s_{t,n}^i\left(\varepsilon\right) d\varepsilon = \kappa^i s_t \quad , i = g, t \tag{25}$$

Family members' nonpecuniary cost or benefit in (24) depends only on investments that they themselves are responsible for. We also impose short sale constraints $s_{t,n}^i(\varepsilon) \geq 0$ on all family members and types of capital.

The family's objective is to maximize the equally weighted sum of utilities across its members. At date t, the family must respect the aggregate budget constraint:

$$\kappa^g c_t^g + \kappa^t c_t^t + s_t = \sum_{i=g,t} \kappa^i \sum_n \int R_{t,n}\left(\varepsilon\right) s_{t,n}^i\left(\varepsilon\right) d\varepsilon + w_t + T_t, \tag{26}$$

where the left-hand side is the overall consumption (by both green and traditional members) and total savings, and the right-hand side represents the total available resources—payoffs from all portfolios chosen by members in the previous period, wage income, and government transfers. The family maximizes its objective by choosing capital and consumption subject to the sequence of members' equity constraints (25) and budget constraints (26).

Portfolio choice and savings. Let λ_t denote the Lagrange multiplier on the family's date t budget constraint (26). Since the family maximizes an equally weighted sum of member utilities and treats all members of type i symmetrically, λ_t also represents the common marginal utility of consumption across members. Let μ_t^i denote the multiplier on type i's date t equity constraint in (25). As is standard in models with short-sale constraints, the optimality conditions for asset holdings take the form of Euler *inequalities*. In particular, the first-order conditions for equity in a firm in sector n operating at emission intensity ε imply

$$\mu_t^t \geq \beta \lambda_{t+1} R_{t+1,n}\left(\varepsilon\right) \qquad \mu_t^g \geq \beta \lambda_{t+1} R_{t+1,n}\left(\varepsilon\right)\left(1 + \gamma\left(\varepsilon_n^* - \varepsilon\right)\right). \tag{27}$$

The left-hand side of each inequality is the marginal cost of investing in any firm. This shadow value of a unit of equity μ_t^i must be larger than the marginal benefit, which appears on the right-hand side. The conditions hold with equality if family member i invests a positive amount in a firm in sector n that operates at intensity ε.

For traditional investors, the benefits from investment are purely pecuniary and hence given by the financial return multiplied by the present value of resources next period $\beta\lambda_{t+1}$. For green investors, by contrast, there is an additional nonpecuniary benefit or cost depending on the emission intensity of the firm they invest in. A convenient feature of our functional form for utility is that the nonpecuniary component is also proportional to the shadow value λ_{t+1}. Pooling of resources by the family implies that the effect of taste heterogeneity is purely myopic: green family members are compensated for the disutility from dirty capital only for one period.

The family's optimal savings and consumption decision depends on the average return on total household wealth R^w_{t+1} implied by individual households' decisions, that is, the value-weighted average returns on all firms. Let $\bar{\varepsilon}_{t,g}$ denote the average emission intensity when equity is weighted by green investors' portfolio weights and let $\bar{\varepsilon}^*_{t,g}$ denote the average of the preference parameters ε^*_n, weighted by green investors' portfolio weights on the different sectors n. Combining first-order conditions, we then have

$$\lambda_t = \beta\lambda_{t+1}\left(R^w_{t+1} + \gamma\kappa^g\left(\bar{\varepsilon}^*_{t,g} - \bar{\varepsilon}_{t,g}\right)\right). \tag{28}$$

The average effective return (including the average nonpecuniary component) must equal the aggregate marginal rate of substitution $\lambda_t/\beta\lambda_{t+1}$. In steady state, this MRS equals the discount rate β^{-1}. The pecuniary return R^w_{t+1} is higher (lower) than the discount rate if green investors' nonpecuniary costs (benefits) dominate *for the average firm held by green investors*. Nonpecuniary costs require returns higher than the discount rate to compensate green investors for the disutility incurred from investing in dirty capital, meaning that green preferences impose a capital tax. Green investors who obtain nonpecuniary benefits, in contrast, require less compensation. In this case, green taste acts like a capital subsidy, reducing the required financial returns on clean investments.

Green representative agent. When all investors have green preferences, $\kappa^g = 1$, they hold all equity. In this case, the green asset pricing equation—the second inequality in (27)—holds with equality for all firms. As a result, all effective returns, including the nonpecuniary component, are equal to the clean rate on a firm with zero emissions

$$R_{t,n}(0) = R_{t,n}(\varepsilon)\left(1 + \gamma\left(\varepsilon^*_n - \varepsilon\right)\right).$$

The key implication is that financial returns must be higher on dirtier firms. Approximating net returns (as in equation (10)), this implies that the financial returns in are linear in emission intensity, $r_{t,n}(\varepsilon) - r_{t,n}(0) = \gamma\left(\varepsilon - \varepsilon^*_n\right)$, with slope equal to the green preference parameter γ. The threshold parameter ε^*_n shifts the entire return schedule of sector n. A higher ε^*_n lowers the return in that sector, effectively subsidizing investment.

A green representative agent who derives only nonpecuniary costs generates the same return schedule as a carbon tax. For zero thresholds, $\varepsilon^*_{t,n} = 0$, we obtain the same cross-sectional returns as with a carbon tax $\tau^c_t = \gamma$ or a capital tax with rate schedule $\tau_t(\varepsilon) = \gamma\varepsilon$. Since the preference parameter γ plays the same role as the carbon tax rate, we measure it in what follows in dollars per ton of CO_2e. The allocation is not exactly the same as in the case of taxes, since holding dirty capital induces utility costs: every period the aggregate tax burden is subtracted from consumption. In other words, the economy with nonpecuniary cost allocates capital and labor like an economy with capital taxes where the government uses tax revenue to purchase consumption goods that are then wasted.[9] We also note that $\gamma\varepsilon$ is the amount of consumption per unit of capital employed at intensity ε that the agent would like to sacrifice to not hold dirty capital.

Heterogeneous agent portfolios. More generally, the investor optimality conditions (27) provide a simple characterization of equilibrium portfolios. First, all firms held by traditional investors must deliver the same return, and this return must exceed the return on any firm held exclusively by green investors. This follows from the first equation in (27), which says that the ratio $\mu^t_t/\beta\lambda_{t+1}$ sets an upper bound for all returns. Since traditional households hold some capital in equilibrium, the upper bound must bind for all the firms they fund. Second, by a similar argument, all firms held by green investors must earn the same *effective* return. Because the nonpecuniary component of green investors' effective return declines with emission intensity, firms with higher emission intensities must deliver higher financial returns to green investors.

Together, these two properties imply a clear segmentation of firm ownership within each sector. Traditional investors only hold the dirtier firms, while green investors only hold the cleaner ones. As a result, the equilibrium return schedule within a sector is piecewise linear, with a kink at some threshold intensity, denoted $\bar{\varepsilon}_n$. Below this threshold, returns rise with emission intensity at a slope of γ; above the threshold, returns are flat, as only traditional investors hold firms at those emission intensities. In equilibrium, green (traditional) investors only hold firms with emission intensities below (above) the threshold. This structure reflects the fact that green investors find higher-emission firms less desirable and demand higher financial returns to hold them. The return schedule, therefore, adjusts to reflect their preferences over the range of firms they fund. Importantly, this effect stems from relative valuation by green investors and holds regardless of whether their preferences involve nonpecuniary costs or benefits.

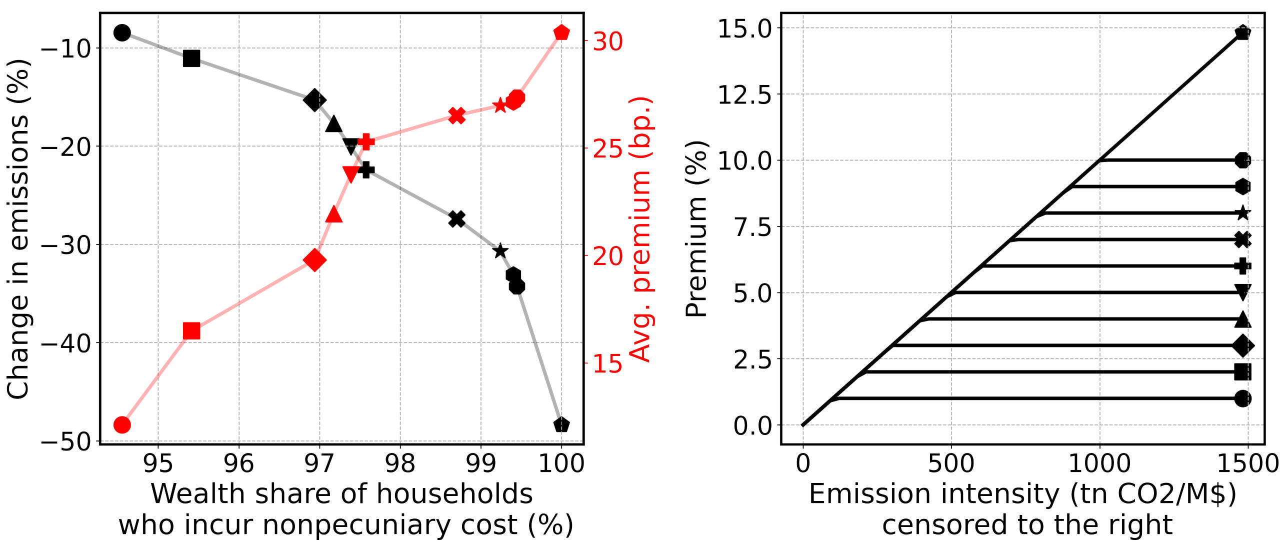
The location of the thresholds $\bar{\varepsilon}_n$ depends on the relative wealth of green and traditional investors, which is captured in our setting by the parameter κ^g. Because green investors must hold all capital below the threshold, a larger κ^g shifts the threshold up: when green investors are relatively wealthier, the segment of the schedule that is responsive to emission intensities is longer, and a smaller share of capital in the economy, particularly the dirtiest firms, earns the same flat return. A key difference from the representative agent case is that the demand for equity is no longer perfectly elastic at the returns provided by the schedule. Instead, equity demand for clean or dirty firms is shaped by the wealth of their respective investor base. In

[9] While the schedule of premia relative to the clean rates $R_{t,n}(0)$, here independent of the sector, is always identical, differences in consumption can affect the level of the clean rate. In steady state, however, clean rates in both cases are equal to the discount rate β^{-1}, so the entire return schedule is identical.

equilibrium, this demand must match the firm-side supply of equity, which itself responds endogenously to the return schedule.

Nonpecuniary benefits versus costs. Whether green investors' preferences reflect nonpecuniary benefits or costs determines the *intercept* of the return schedule. Consider first the case of nonpecuniary costs in all sectors, that is $\varepsilon_n^* = 0$ for all n. In this case, there exists an economy-wide clean rate $R_t(0)$, which is the return earned by the cleanest firms with zero emissions. All other firms must deliver higher returns to compensate green investors for the disutility of their emissions. As shown in the right panel of Figure 5, the return schedule rises linearly with emission intensity up to the threshold and remains flat beyond it. Notably, firms with emission intensities above the threshold—owned solely by traditional investors—also earn returns strictly above the clean rate, even though traditional investors are indifferent to emissions. While these investors would be willing to hold dirty firms at lower returns, high equilibrium returns on the dirtiest firms are necessary for markets to clear. The dirtiest firms must offer sufficiently high returns to prevent traditional investors from reallocating their capital to slightly cleaner firms held by green investors, which offer a premium over the clean rate.

Figure 5: Equilibria with nonpecuniary costs (γ = \$100/tn CO_2e)



Note: Each symbol represents the equilibrium of an economy with a different share of green investors κ^g, with γ chosen s.t. a representative green investor generates a \$100 carbon tax. Left panel shows change in emissions relative to the baseline with no green investing (black line, left axis) and the average premium over the clean rate paid by a firm that generates zero emissions (red line, right axis). Right panel shows equilibrium return schedules for each economy by plotting premia relative to the clean rate. Each schedule consists of a sloped segment starting at its symbol and a flat segment at high intensities.

Now suppose instead that green investors derive nonpecuniary benefits from investing in a single preferred sector n. In this case, the cleanest firms in that sector earn returns that are not only lower than those of dirtier firms within the same sector, but also lower than the common return earned across all other sectors. In the preferred sector, we again have a threshold intensity beyond which the returns flatten. A new feature with sector-specific preferences is that the location of the threshold now depends not only on the wealth of green investors but also on the relative size and emissions distribution of the preferred sector compared to the other sectors in the economy. In particular, if there are very few green investors relative to the supply of clean capital in the preferred sector, there may be a jump in the return schedule at the threshold emission intensity. Green investors buy the cleanest firms, with emission intensities up to the threshold, and obtain nonpecuniary benefits that reduce the financial returns. Traditional investors hold dirtier firms beyond the threshold, which offer flat returns that are discretely larger.

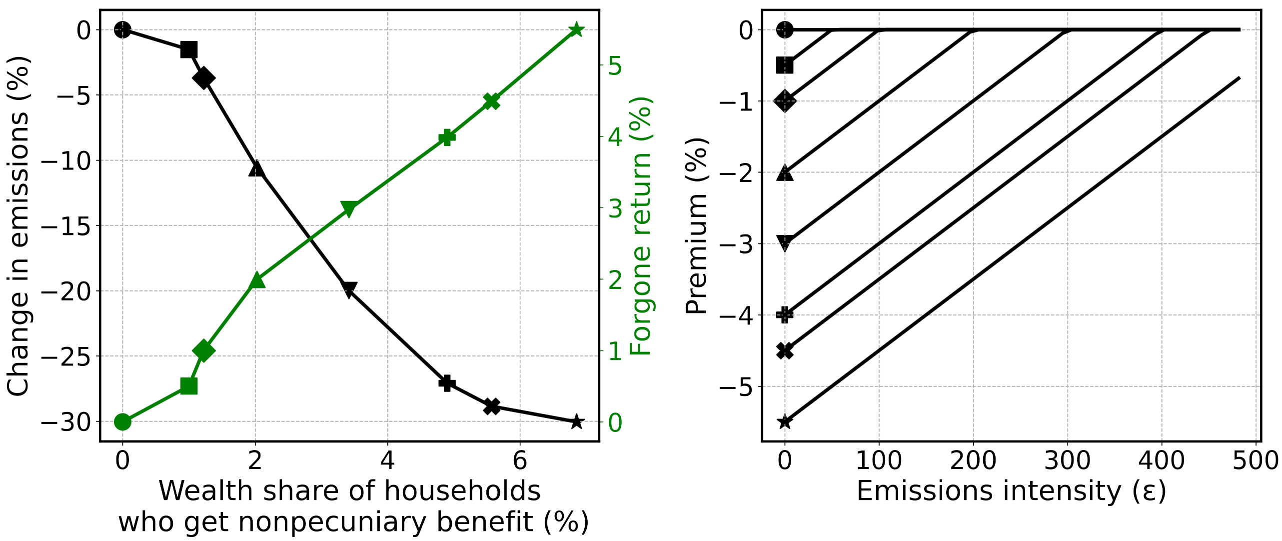
Our goal in this section is to clarify the potential of a small group of investors who obtain nonpecuniary benefits to reduce emissions, as opposed to providing an exhaustive characterization. We thus focus on economies where the return schedule is continuous at the threshold: we choose wealth shares such that green investors hold only electricity firms and generate a continuous equilibrium return schedule. The right panel of Figure 6 illustrates the class of return schedules for the electricity sector we consider. The benchmark rate for measuring premia here is the rate earned by traditional investors in equilibrium, which is also the clean rate for all sectors other than electricity.

Different schedules start at different intercepts, but all share an increasing piece with the same slope and flatten out once they reach zero. The variation in intercepts reflects the magnitude of the nonpecuniary benefits of green investors from holding the cleanest electricity firms. Compared to the patterns in the right panel of Figure 5, the key new feature is that relatively (but not perfectly) clean electricity firms pay lower returns than firms in all other sectors (clean or not). As a result, pay, the return schedule is responsive to emission intensity even for electricity firms with relatively high emissions.

Firm behavior. The firm problem in the economy with green investor preferences is the same as before. In particular, firms face return schedules that depend on their emission intensity and take these schedules into account when choosing their production plans. A technical difference is that, when the premium schedule is concave, as in Figures 5 or 6, the firm problem is no longer convex. First-order conditions are therefore no longer sufficient to characterize the solution. However, a solution still exists and is easy to characterize, since the schedule faced by any firm depends on a finite number of segments. For any given schedule, we solve the firm problem by taking cases: we check the optimal solution within each segment and compare solutions across cases.

Another interesting consequence of a concave return schedule is that the problem of a multi-product firm is no longer equivalent to the weighted problem of its single-product subsidiaries. For example, an electricity firm that owns both a zero-emission solar installation and a gas-fired power plant may face worse terms in funding markets than two stand-alone clean and dirty subsidiaries. In other words, it can make sense for a "mixed" firm with clean and dirty operations to spin off one of the two subsidiaries. We thus work in this section with single-

Figure 6: Equilibria with nonpecuniary benefits from electricity (γ = \$100/tn CO_2e)



Note: Each symbol represents the equilibrium of an economy with a different share of green investors κ^g, all with γ=\$100/tn CO_2e, but different ε_n^* for the electricity sector. Left panel shows change in emissions relative to the baseline with no green investing (black line, left axis) and difference in return on wealth between traditional and green investors (green line, right axis). Right panel shows equilibrium return schedules for the electricity sector of each economy by plotting premia relative to the return earned by traditional investors. Each schedule consists of a sloped segment starting at its symbol and a flat segment at high intensities.

technology firms. In particular, all electricity firms employ only one type of fuel. We view this as a conservative assumption that makes sure that no results are driven by arbitrary restrictions on capital structure.

Equilibrium An equilibrium consists of an allocation and prices, including a return schedule, so that all households and firms optimize and markets clear. The return schedule is determined jointly with the distribution of capital. On the household side, the exogenous distribution of member types determines how much equity is held by green versus traditional investors. Within the holdings of each type, the demand for equity by intensity is perfectly elastic, provided that the Euler equations (27) hold. On the firm side, a return schedule gives rise to a collection of production plans and hence a distribution of equity by emission intensity. In equilibrium, the distributions and returns are consistent.

5.2 Quantifying the impact of heterogeneous preferences

Our goal is to assess how small amounts of heterogeneity matter for both the return distribution and equilibrium emissions. We focus on green investors with a strong taste for clean capital. We set the preference parameter γ so that if all investors were green ($\kappa^g = 1$), their behavior would work like a \$100 carbon tax in the case of nonpecuniary costs or benefits. We study two sets of counterfactuals. The first explores the robustness of an equilibrium in which most investors incur nonpecuniary costs (all intercepts are zero, $\varepsilon_n^* = 0$). The second set of exercises assumes that there is a positive intercept in all subsectors of electricity generation. As before, we consider comparative statics of steady states.

Nonpecuniary cost. Figure 5 illustrates how emissions respond to changes in the share of green investor households. The horizontal axis focuses on a range of the share κ^g above 95%, where the vast majority of households have strong green preferences. At the far right point, $\kappa^g = 1$, we recover the green representative agent benchmark, which achieves an emission reduction close to 50%— equivalent to implementing a $100 carbon tax. Moving left, we plot steady-state outcomes for lower values of κ^g, with the corresponding emission reductions shown by the solid black line. The corresponding schedules of returns are marked in the right panel with the same symbol. The red symbols further show the average return premium, in basis points, measured along the right vertical axis. The main result in the figure is that **emissions are extremely sensitive to a small drop in the share of green investors below 100%.** Even a one percent lower share lowers the emission reduction to 22pp, close to one half. A five percent lower share means the emission reduction is 10pp or one fifth.

This result is driven by the extreme skewness of the distributions of both emissions and emission intensities. A carbon tax achieves large emission reductions precisely because it creates strong incentives for the dirtiest firms to lower their emission intensities. Replicating returns can do the same, but only if they continue to rise steeply in the right tail of the intensity distribution. A small number of indifferent investors removes this effect. As we have seen, those investors must earn the highest equilibrium returns, and are not responsive to intensity, so the return schedule flattens out. As a result, the strongest incentives targeting the dirtiest firms disappear. Since emissions themselves are also heavily skewed, there is a large cost in terms of total emissions.[10]

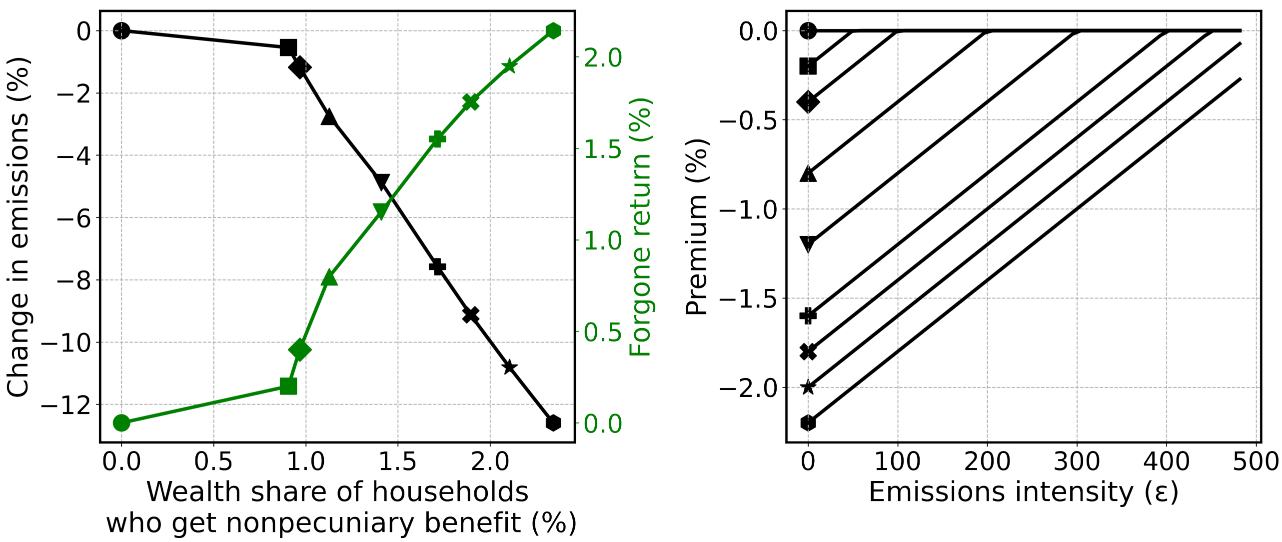
Nonpecuniary benefits from electricity. Figure 6 analyzes economies with a small share of green investors, again measured along the horizontal axis. The benchmark case is the leftmost point, where $\kappa^g = 0$, corresponding to a representative agent without a carbon tax. Unlike the previous exercise, green investors here derive nonpecuniary benefits from holding equity in electricity firms. This setup requires specifying two preference parameters: the slope γ and the intercept ε_n^*. We study a set of economies with continuous return schedules by jointly varying κ^g and ε_n^*, so that the wealth of green investors is just enough to purchase all electricity capital below the threshold. These parameter combinations imply the return schedules shown in the right panel of Figure 6. The left panel displays, as green symbols, the foregone financial return per unit of wealth for the green investors, measured in percentage points along the right vertical axis.

The main takeaway from the economies with nonpecuniary benefits is that **a small wealth share of green investors can lead to substantial emission reductions—provided their prefer-**

[10]Put differently, the return premium can be interpreted as a carbon tax rate times an emission intensity. When the premium flattens, intensity continues to rise, so the implied carbon tax rate effectively declines.

ences are focused on a dirty sector with significant substitution potential, such as electricity. Remarkably, with just a 2% wealth share, emissions fall by more than 10% relative to baseline. When green investors hold 6% of total wealth, emissions decline by over half of what a \$100-per-ton carbon tax would achieve. The key effect is that electricity firms have strong incentives to expand clean production. The return schedule subsidizes clean electricity generation relative to all other sectors. The green line in Figure 6 records the amount of subsidy along the right vertical axis, the cost to green investors for holding a unit of capital. Of course, since the incentives, and hence equilibrium subsidies, are now provided by a few green investors, the foregone return per unit of wealth for those investors is a lot larger than the average premium in the nonpecunary cost case above. Still, losses remain moderate, on the order of a few percentage points.

Figure 7: Equilibria with nonpecuniary benefits from electricity (γ = \$40/tn CO_2e)



Note: Each symbol represents the equilibrium of an economy with a different share of green investors κ^g, all with γ=\$40/tn CO_2e, but different ε_n^* for the electricity sector. Left panel shows change in emissions relative to the baseline with no green investing (black line, left axis) and difference in return on wealth between traditional and green investors (green line, right axis). Right panel shows equilibrium return schedules for the electricity sector of each economy by plotting premia relative to the return earned by traditional investors. Each schedule consists of a sloped segment starting at its symbol and a flat segment at high intensities.

5.3 The role of short sale constraints

Short-sale constraints are important for the results in this section. In our model, they generate return schedules with different segments, a flat segment where capital is held by traditional investors, and a sloped segment where capital is held by green investors. Only the sloped segment provides incentives to reduce emission intensities, so green investing is effective when many firms either lie on this segment or can adjust to reach it. We briefly discuss robustness of our results to alternative assumptions.

Shorting fees. To generate Figure 6, we assumed a strong taste for subsidizing electricity on the part of green investors by setting the parameter γ to \$100 per ton. As a result, return differentials up to 5pp for the cleanest firms emerged in equilibrium. This number is large relative to typical shorting fees, although such fees have increased in recent decades. The conventional wisdom at the turn of the millennium was that shorting fees are small: for example, D'Avolio (2002) shows that fees on most stocks are less than 1%, and that only about 10% stocks are hard to borrow and involve much higher fees. More recently, Muravyev et al. (2025) report an average shorting fee of roughly 2% and double-digit shorting fees in the tail of the distribution. Engelberg et al. (2018) documents substantial time variation in shorting fees and high persistence. As a consequence, there is substantial risk in shorting stocks over longer horizons.

To clarify what is possible with lower return differentials, we redo the nonpecuniary benefit exercise with a lower preference parameter γ of \$40 per ton. Figure 7 presents results analogous to Figure 6. With this parametrization, the right panel shows that essentially all return schedules feature premia below 2pp in absolute value, that is, within reasonable bounds for shorting fees observed recently. As one would expect, the emission reduction is now smaller as the incentives provided to dirty electricity companies are weaker. Nevertheless, investors with 2% of wealth are able to generate emissions that are 12% lower than in the baseline case without any green investing.

Risk aversion. In our deterministic model, a stark division of the return schedule into segments arises because assets are perfect substitutes, so any difference in tastes for green assets implies that only one investor type holds the asset whereas the other hits the short-sale constraint. An extension of the setup to risk-averse agents can give rise to equilibria where short-sale constraints do not bind, or bind for fewer assets. As a stark example, suppose there are no short-sale constraints at all, there are shocks to firms' TFP, and investors are equally risk averse, but green investors incur nonpecuniary costs from dirty portfolios, a case often considered in the literature. In equilibrium, green (traditional) investors still hold more clean (dirty) firms, as in our model. The difference is that they also short dirty (clean) firms.

In a setup with risk aversion and no shorting, equilibrium returns typically reflect wealth-weighted averages of returns that would obtain if only one type of investor was present, and in particular a wealth-weighted average of the nonpecuniary cost. One prominent force of this section, that investors with a small wealth share matter disproportionately, is then muted. A large share of green (traditional) investors would tend to push returns close to the case of a representative green (traditional) investor. In addition, returns could reflect compensation for risk – details here would depend on the correlation of returns across sectors and firms, and on how risk is shared across investor types.

Although these caveats which might affect quantitative result, the main takeaways from this section are likely to carry over to a setting with risk. Consider our first result that when preferences reflect only nonpecuniary costs, green investing does not effectively reduce emissions. As we have seen, preferences that replicate a \$100 carbon tax require the willingness to sacrifice double-digit annual returns on the dirtiest firms. A large enough coalition of such investors may not assemble even if short selling is free. Moreover, when return differentials become large, short-sale constraints bind also in models with risk, so the sorting mechanism reemerges. For example, Aron-Dine et al. (2024) study a quantitative model with heterogeneous risk-averse agents and nonpecuniary costs where sorting occurs because investors disagree about expected returns about green assets.

Our second result is that a small coalition of green investors can have impact if they favor clean electricity firms. In a model with risk and short-sale constraints, the same mechanism is relevant: if green investors bid up prices of electricity firms so average returns are lower, traditional investors will find those firms less attractive to hold. Since, traditional investors can be well-diversified even if they do own electricity firms, a tiny share of capital, their incentive to hold such firms is almost as small as in our model. A difference is that the cost to green investors of focusing on electricity may be larger if investors also forego diversification benefits. While this requires recomputing what willingness to pay is required, it leaves in place the principle that a small share of green investors can matter.

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APPENDIX

A Input-Output structure

Here we detail the input-output structure of the quantitative model used in Section 4. Much of the production structure follows the multisector model developed by Yuan et al. (2019). We depart from their setup to accommodate firm-level heterogeneity in the electricity sector and to match the slightly different breakdown of our sectoral data. Table 6 lists all sectors in our model.

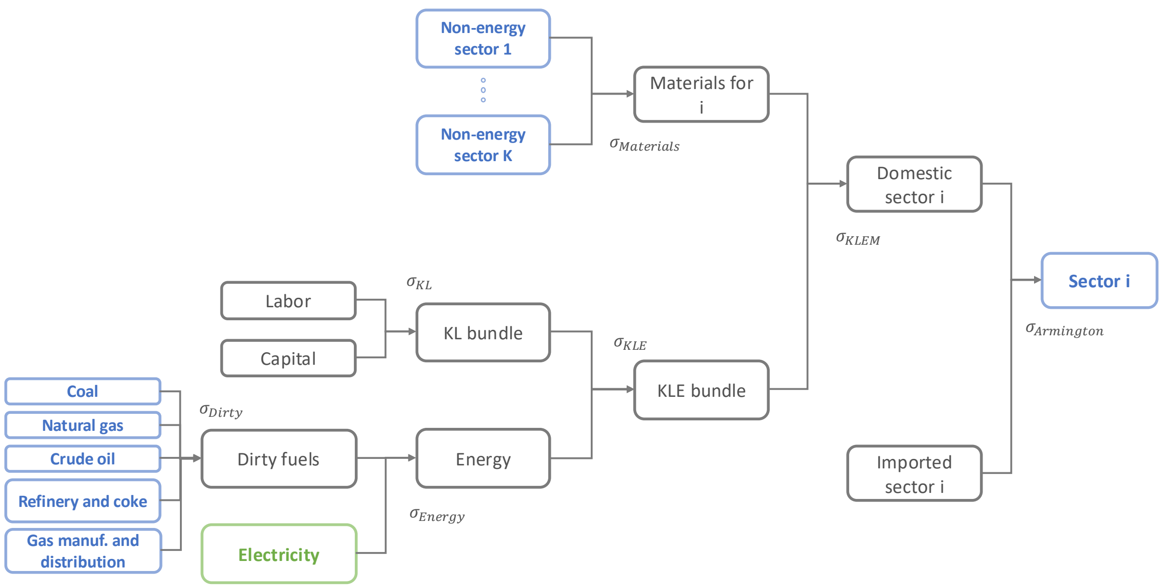

Figure 8: Input-output structure of a generic sector

Figure 8 describes a generic non-electricity sector. Each node represents an intermediate input and each arrow an input-output linkage of a sector-specific production function. Each production stage (illustrated by a set of arrows that point to a single node) is described by a CES production function. For easier reference, we include the label of the CES elasticity of substitution σ at each stage of production. For example, in the lower left ocrner of the diagram, dirty fuels are combined into a dirty fuel bundle in a CES nest with substitution elasticity σ_{Dirty}, which in turn is combined with electricity into an energy bundle in a CES nest with elasticity σ_{Energy}. Elasticity numbers are collected in Table 7 below.

Beyond energy, the nested CES structure for a generic sector has several additional layers. Labor and capital are combined to make a "KL" bundle, which is then combined with the energy bundle to produce "KLE". All non-energy related goods are combined into a materials bundle, which is combined with the KLE bundle to produce the final output of the domestic

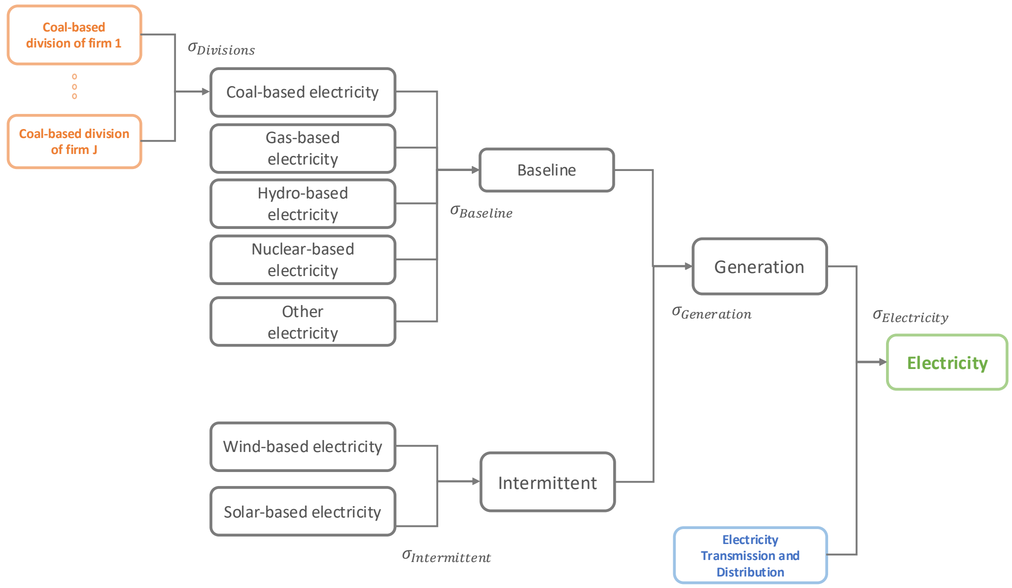

Figure 9: Input-output structure of electricity

sector. Finally, domestic output is combined with imported goods to produce the total supply of the good made by the sector. This generic structure applies to the 60 non-energy sectors in the model. It also applies to the electricity transmission and distribution (ETD) sector, 4 non-carbon electricity sectors, and all 5 dirty fuel sectors. Nodes with a blue border highlight which products have a generic production structure.

Figure 9 describes the input-output structure of the electricity sector. Electricity production starts from 7 electricity varieties: coal-based, gas-based, hydro, nuclear, solar, wind, and other[11]. Each electricity type is aggregated in two groups based on technological constraints on storage and readiness-to-dispatch upon changes in demand. We bundle solar and wind as intermittent sources, and the rest as baseline sources. Intermittent and baseline sources are combined into electricity generation, which in turn is combined with the output of the ETD sector to produce the total supply of electricity in the economy. Green-bordered nodes highlight the final electricity sector.

Carbon-based electricity varieties have a production function slightly different from the generic sector structure. Leveraging firm- and division-level micro-data, as described in C below, we include an extra production layer in each electric variety to account for firm level heterogeneity. Figure 10 describes the structure of a single electric variety (for example, coal-based electricity). Each 'division' represents a firm-variety pair. The output of each division is bundled into a domestic electric variety. The rest of the input-output structure replicates the

[11]Other is a residual that will absorb electricity production based on oil, biomass, geothermal and any other source not considered in our model.

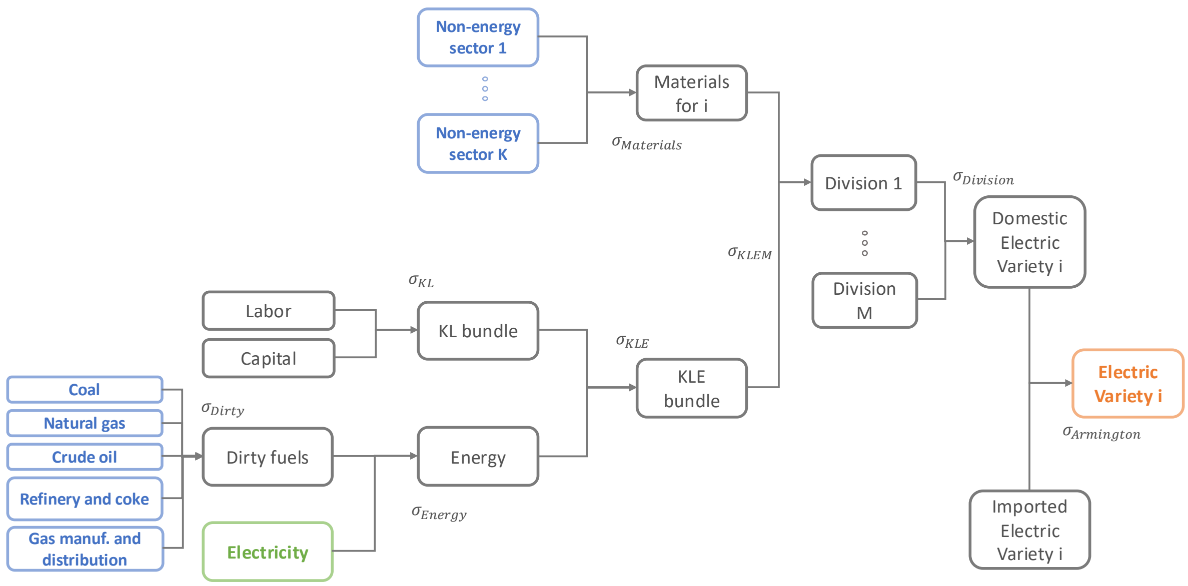

Figure 10: Input-output structure of a generic electric variety

generic sector. Orange-bordered nodes denote an electric variety.

Finally, Figure 11 illustrates the structure of the final demand. A "fudge" good bundles output of all non-energy sectors, except for housing services and household vehicles. This good is used in the production of the final consumption good, and it is directly used as capital and exported. In the case of final consumption, the "fudge" good is combined with two additional goods: housing services and household vehicles. In the case of exports, "fudge" is combined with exported energy goods.

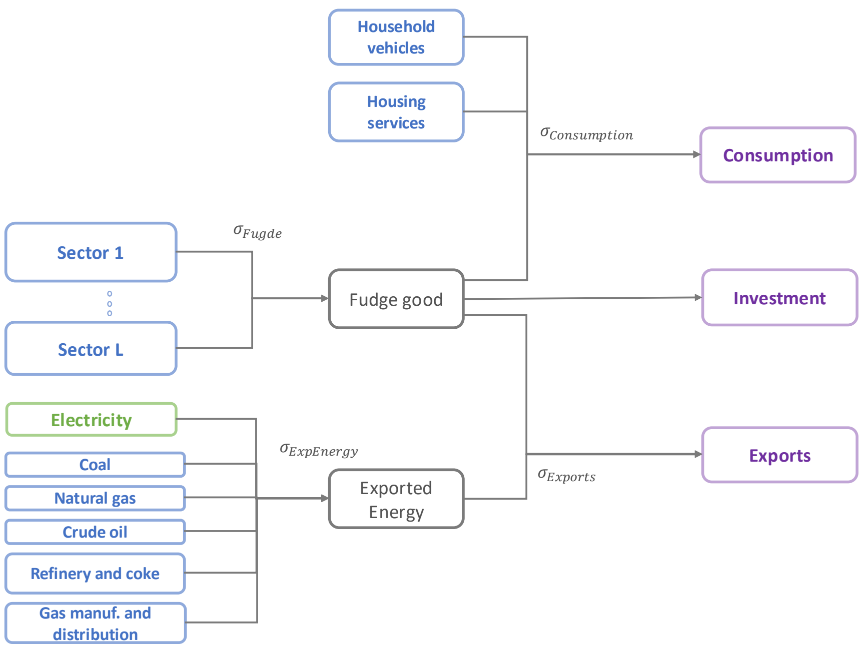

Figure 11: Input-output structure of final demand

Table 6: Sectors and Aggregators

Sectors					Aggregators
Primary	**Carbon Fuels**	**Manufacturing**	**Services**	**Electric Varieties**	
Paddy rice	Coal	Bovine meat products	Water	Coal-BL	Electricity
Wheat	Oil	Other Meat products	Construction	Gas-BL	Final Demand
Other cereal grains	Gas	Vegetable oils and fats	Trade	Other-BL	
Vegetables, fruit, nuts	Gas manufactur	Dairy products	Accommodation	Hydro-BL	
Oil seeds	Refinery	Processed rice	Commercial land transport	Wind-BL	
Sugar cane, sugar beet		Sugar	Water transport	Solar-BL	
Plant-based fibers		Other Food products	Air transport	Nuclear-BL	
Other Crops		Beverages and tobacco products	Warehousing		
Cattle		Textiles	Communication		
Other Animal products		Wearing apparel	Financial services nec		
Raw milk		Leather products	Insurance		
Wool, silk-worm cocoons		Wood products	Real estate activities		
Forestry		Paper products, publishing	Other Business services		
Fishing		Chemical products	Recreational		
Other Mining		Basic pharmaceutical products	Public Administration		
		Rubber and plastic products	Education		
		Other Mineral products	Human health and social work		
		Ferrous metals	Housing services		
		Other Metals	Household vehicles		
		Metal products	Electricity Transmission and Distribution		
		Computer, electronic and optics			
		Electrical equipment			
		Other Machinery and equipment			
		Motor vehicles and parts for firms			
		Other Transport equipment			
		Other Manufactures			

B Data

In this section, we describe our data sources, and how we clean the data and map them to the model. Our main sources of data are GTAP 11 database from the *Global Trade Analysis Project*, and Trucost and Compustat databases from *S&P Global*. We also describe some complementary data sources, used to pin down specific parameters of the model.

GTAP 11 database GTAP 11 is a dataset developed by the *Global Trade Analysis Project*. GTAP is a global network of researchers conducting quantitative analysis of international trade. It is coordinated by the Center for Global Trade Analysis in Purdue University's Department of Agricultural Economics. For further reference, see (Aguiar et al., 2022). It collects in an unified and consistent framework annual transactions across countries and economic sectors, based on official national accounting and trade statistics. It also includes physical transactions of energy-related goods, and their related CO_2 emissions, based on official trade balances and consistent with 2006 IPCC guidelines Tier 1. Energy and emission related information are included in two satellite datasets called GTAP-Power and GTAP-E, respectively.

The most disaggregated version of GTAP 11 reports transactions of 141 countries and 76 sectors. There are 17 are energy-based goods. The 12 electricity-producing energy sectors comprise 7 *base load* (BL) technologies (NuclearBL, CoalBL, GasBL, HydroBL, OilBL, WindBL, and OtherBL), 4 *peak load* (P) technologies (GasP, OilP, HydroP, and SolarP) as well as a transmission and distribution sector (TnD). The 5 carbon-based energy sectors are Coal, Gas, Crude Oil, Petroleum and Coal Products, as well as Gas Manufacture and Distribution. Physical quantities are reported for energy-related goods, except for transport and distribution of electricity. Emissions are reported for carbon-based energy goods only. The year of reference is 2017. All monetary values are reported in million 2017 US dollars, energy physical units are in thousands of tons of oil equivalent, and emissions are in million of tons of CO_2.

Data extraction. We extract the following data for the United States from the GTAP 11 database. We obtain the monetary value of (i) intra-industry and final purchases (consumption, investment, government and exports) of domestic and foreign goods, (ii) factor purchases (skilled labor, unskilled labor, capital, land and natural resources), as well as taxes and subsidies of domestic sectors and finally (iii) residuals at sector level that accounts for statistical differences between total sales and costs. By construction, total sales and costs of each domestic sector are equal, up to the residual term. We further extract physical quantities of domestically produced and imported energy-related goods, purchased by domestic sectors and the final demand as well as emissions of CO_2 related to the use of energy-related goods.

Mapping data to model: domestic intermediates. In order to calibrate the model, we need observable counterparts for factor shares and input shares of all goods. We measure the value added of a domestic sector as the sum of all factor costs originally reported (skilled labor, unskilled labor, capital, land, and natural resources), plus taxes and subsidies paid by the sector, and statistical differences between total sales and costs. We then split value added into labor and capital, in proportion to the sum of skilled and unskilled labor costs relative to the sum of capital, land and natural resources.

International trade. As part of the input-output matrix, GTAP records the value of imports of every good by every domestic sector. We aggregate across buyer sectors to obtain the total domestic sales of the imported good. On the demand side, we aggregate purchases across origins, so all buyers – whether households or firms of different sectors – buy a single Armington bundle of any given good, instead of choosing buyer-specific combinations of local and imported goods. In addition, our model assumes a single price vector for energy-related goods (dirty fuels and electric varieties) for which we also observe quantities. We compute prices by dividing the value of total sales of a good by the total quantity good sold. Based on this normalized price, we then redefine quantities at the buyer-seller level to match values. This step removes small discrepancies in reporting of international trade.

Electricity. We simplify the electricity sector by reducing the originally reported 12 electricity-producing energy sectors to 7 electricity varieties. In particular, we merge GasP and GasBL into Gas, OilP, OilBL and OtherBL into Other and HydroP and HydroBL into Hydro. We further add an aggregator (CES nest) called "electricity" that collects the physical output of the 7 electric varieties and combines revenues of these varieties plus the transmission and distribution sector. We replace each purchase of an electric variety in the original dataset with a purchase of this newly created aggregate electricity sector. We normalize the price paid across sectors to match the ratio of total sales to total quantity of electricity sold.

Vehicles and housing. We define two automobile sectors: one that produces vehicle services consumed by households, and another that produces cars as an intermediate input for firms. The latter sector is derived by first computing the share of automobiles purchases as an input by domestic sectors other than households, and then multiplying GTAP automobile sector input and factor costs by that share. Output of the vehicle services sector consists of the remaining share of auto sector output, plus GTAP final consumption of petroleum and coke. ELEC We further create a housing services sector by adding to GTAPS's dwelling sector all consumption of energy by the final demand, except for petroleum & coke, which is assumed to power cars.

Consumption, exports and capital. As displayed in Figure 11, we bundle all non-energy, non-car, non-housing goods purchased by GTAP's final demand sector into a single *fudge* good. The fudge good is the numeraire for the quantiative exercises and serves three purposes. First, it is combined with housing services and vehicles services to produce final consumption. In addition, it is directly installed as capital and exported. The quantiative exercises thus abstract from difference in goods baskets used to make sector-specific capital goods or exports. Robustness analysis suggests that such differences do not have an important effect on the results.

BEA capital stock and depreciation. To complement GTAP value and input numbers, We extract depreciation and capital stock information from *Fixed Asset Tables* from *Bureau of Economic Analysis* (BEA) to construct sector-specific depreciation rates. For consistency with the rest of the data sources, we use current-cost measures of 2017. We extract capital stocks from *Table 3.1ESI* at NAICS level. We add government capital stocks from *Table 1.1.* Annual depreciation is from *Table 4.4ESI* at NAICS level and depreciation of government assets is from *Table 1.3.*. We match BEA sectors to our model sectors and compute the depreciation rate of each sector as the ratio of depreciation to the capital stock.

C Firm- and division-level data for the electricity sector

Firms and divisions. Trucost is a subsidiary of *S&P Global* that provides data on environmental impact of companies. Trucost breaks down electricity generation of every firm by the type of fuel used, in particular, coal, gas, solar, geothermal, hydro, oil, wind, nuclear, landfill, biomass, LNG, tidal, and other. We also observe emissions per type of fossil fuel, that is, coal, gas, oil, LNG, and LPG. We can therefore divide up firms into *divisions* that aggregate all generation of the same firm that use the same fuel. To map fuel types to our model, we aggregate Trucost's geothermal, landfill, biomass, tidal, LNG and LPG and other energy types into the *other* category of the model.

We merge TruCost data to Compustat using the internal *S&P Global* firm identifier *gvkey*. We focus on US-based active companies with positive electricity generation in 2017. We measure enterprise value as the sum of market capitalization ("mkval"), long-term debt ("dltt"), short-term debt ("dlc") and preferred stock ("pstkrv") less cash ("che"). We end up with a dataset of 45 energy-producing firms and 203 divisions. For each division, we observe enterprise value at the firm level, as well as generation by type of fuel and emissions by type of fuel at the division level. We impute division-level enterprise value in proportion to the division-level generation of each firm.

Table 7: Elasticities of substitution

Generic sector (Figure 8)		**Final demand (Figure 11)**	
Parameter	Value	Parameter	Value
$\sigma_{\text{Armington}}$	2.5	$\sigma_{\text{Consumption}}$	1
σ_{KLEM}	0	σ_{Fudge}	1
σ_{KLE}	0.4	$\sigma_{\text{ExpEnergy}}$	0
$\sigma_{\text{Materials}}$	0	σ_{Exports}	0
σ_{KL}	1		
σ_{Energy}	0.5		
σ_{Dirty}	1		

D Model quantification

Our quantification of the model follows standard practice in the literature. We assume CES production functions and calibrate substitution elasticities based on values in existing models.

The weights in the production functions are determined from a "social accounting matrix" that captures the flow of inputs and outputs across sectors and firms. For non-energy goods, we normalize units by setting their prices equal to one in an initial equilibrium. This choice is without loss of generality as long as counterfactuals focus on percentage changes in quantities and prices, rather than physical units, as we do for non-energy goods in our model.

For energy goods, where emissions depend on physical units, we rely on data for both prices and quantities. The GTAP database reports quantities of emission-generating energy goods in units of *coal equivalents*, allowing us to compare energy content across different fuels. This standardization underlies the construction of Table 1. For nuclear, solar, and wind electricity, we only observe generation data, not the energy content of their inputs. To make the table, we measure energy content using the *substitution method*, that is, we divide generation by a factor of approximately .4—treating these technologies as if they were as inefficient as fossil fuels. This convention is not relevant for quantifying production functions, since those include only inputs with positive prices.

We use observable prices for energy goods, labor, and capital. For capital, we measure user costs as the sum of the interest rate and the depreciation rate, as described above. Given the CES nesting structure in production, we can back out nest weights and TFP for each sector using sectoral data on gross output, material inputs, and labor compensation by sector. In particular, expenditure shares identify the nest weights, while TFP is pinned down by equating the unit cost of a sector to its price.

Although our model assumes balanced trade, U.S. data in 2017 show a trade deficit of about 2.8% of GDP. To reconcile this with aggregates, we scale down the final good input to consumption and increase exports. This adjustment leads to a slight understatement of consumption in the model. However, because our analysis focuses on comparative steady states, this convention is not essential for our results.

Technology parameters. Key elasticity values are listed in Table 7. For a typical non-electricity sector, the location of each elasticity in the nesting structure is displayed in Figure 8. Domestic and imported varieties are substitutes, with an Armington elasticity of 2.5. The domestic variety is produced using materials and a *KLE bundle* that combines capital (K), labor (L), and energy (E). Materials and the KLE bundle must be combined in fixed proportions. Within the KLE bundle, substitution elasticities are relatively low between the capital-labor composite and energy, as well as between electricity and a bundle of dirty fuels. We assume an elasticity of one between capital and labor, as well as among the different dirty fuels.

The production technology for the electricity sector differs from that of other sectors, as it is designed to accommodate detailed division-level data. For each fuel type, we specify a nest over multiple varieties, where each variety is producted using materials and a KLE bundle. The number of varieties per fuel type equals the number of divisions observed in the TruCost dataset, plus one residual variety used to reconcile the division-level data with sectoral aggregates from GTAP. We further introduce an aggregate electricity sector that combines electricity generated from different fuels. This aggregation accounts for the imperfect substitutability across fuel types, and incorporates the additional resources required to operate and maintain the electricity grid.

At the division level, we observe electricity output and fuel inputs, but not other inputs such as materials and labor. We describe each division's production technology using nested CES production functions with common elasticities of substitution and common relative weights on capital, materials, and labor. However, we allow the weight on fuel relative to the other inputs to vary across divisions. We calibrate the relative weights of capital, labor, and materials to the aggregate data for all plants with the same fuel from GTAP. We then adjust the weight on fuel at the division level to match observed emission intensities relative to output, thereby capturing heterogeneity in fuel use across divisions.

The elasticities for electricity varieties, illustrated in Figure 9, are largely consistent with those of a generic sector, with a few exceptions. We use a lower Armington trade elasticity of .3 for electricity. In our baseline, we also assume that nuclear and hydro power operate with fixed capital stocks. For these technologies, we set substitution elasticities for the KL and the KLE bundle to zero. We thus ensure that electricity from nuclear and hydro power remains constant. For the aggregation of electricity, we assume an elasticity of 6 for substitution among divisions using the same fuel, and an elasticity of 10 for substitution across different fuels and between generated electricity and distribution services. Our robustness exercises in Section 4.3 vary these numbers.

The right-hand side of Table 7 lists elasticities relevant for the aggregation of goods, corresponding to the nesting structure shown in Figure 11. We define the *fudge good* as a Cobb-Douglas bundle of intermediates that represents all capital goods and the export good. Accordingly, the production functions $\tilde{g}$ and h^n are identical. The fudge good serves as numeraire in our calibration. The consumption good is a Cobb-Douglas aggregate of the fudge good, vehicle services consumed by households, and housing services.

Benchmarking to EMF 32 meta-study. The Stanford Energy Modeling Forum (EMF) conducted a coordinated analysis of various carbon tax scenarios using 11 dynamic computable general equilibrium models specifically designed for evaluating environmental policy. Results were published in a special issue of *Climate Change Economics*, with headline numbers summarized in McFarland et al. (2018), henceforth McF, with additional detail in Macaluso et al. (2018).

The scenarios analyzed in the meta-study are broadly comparable to our exercise: the carbon tax is applied to U.S. CO_2 emissions from fossil fuels, with no concurrent policy changes abroad, and tax revenues are rebated to households. However, there are important differences. The EMF models prescribe a baseline with economic growth and a dynamic path for the carbon tax. The models also have richer dynamics than ours, in particular adjustment costs or explicit tracking of vintages of capital goods.

We focus on the scenario of a $50 per ton carbon tax that continues to grow at one percent after the initial introduction. Emissions trajectories in McF Figure 3 show that most of the

EMF models feature fast adjustment to a state where emissions are close to constant. In many cases, it takes only one or a few periods for the model to reach a flat path. Similarly, the mix of primary energy is close to constant after the tax is imposed. These patterns suggest that transition dynamics are not a central feature in the leading models. Therefore, it is reasonable to compare a version of our exercise—differences of steady states with and without a $50 carbon tax—to the models' predictions for the state after their initial short adjustment. This supports the validity of using comparative statics across steady states for evaluating medium-run policy impacts.

Our model delivers results that are quantitatively in line with the typical outcomes reported in the meta-study along several key dimensions: (i) emission reductions overall and by broad sector (ii) primary energy and electricity consumption and (iii) output loss and carbon tax bill.

Specifically, McF Figure 4 reports percentage reductions of emissions relative to a no-tax baseline, both total and broken down by electricity, transport as well as a combined category of households & industry. Across the 11 EMF models, economy-wide emission reductions range from 20% to 40%. Sectoral reductions fall between 50% and 70% for electricity, remain below 15% for transport, and lie between 15% and 30% for households & industry. In comparison, our analysis produces a 33% reduction in aggregate emissions, with sectoral contributions of 62% from electricity, 14% from transport, and 24% from the combined households and industry sectors. These results place us squarely within the range of the EMF models.

Regarding primary energy consumption, all EMF models project strong reductions in coal use—ranging from 30% to 90%—and modest reductions in oil use, below 10% (Macaluso 2018, Figure 2). Our results fall well within these ranges, with a 70% reduction in coal consumption and a 7% reduction in oil use. In contrast, EMF model predictions for natural gas vary widely: some show a 20% increase, while others predict a decline of up to 50%. Our results show a 35% reduction in gas use. This is partly driven by substitution toward renewable energy. However, even in the robustness scenario that effectively shuts down such substitution, gas use still falls by 20%. A key factor behind this result is the heterogeneity of power plants in our model. By allowing substitution away from the least efficient gas-fired electricity varieties, we capture an important channel for reducing gas use——even when renewables are constrained.

Across EMF models, aggregate energy and electricity consumption decline by 4–15%, as shown in Macaluso et al. (2018), Figure 5. In our model, agents consume 11% less energy and 6% less electricity——well within this reported range. The EMF models further report a few basis points lower growth per year on average over 25 years relative to the reference scenario. This number aligns closely with our result of a .7% drop in steady-state consumption, which translates to a similar cumulative effect over the medium run. Finally, the carbon tax revenue reported in the EMF models stabilizes after the initial adjustment phase and averages $200-$250 billion per year in 2010 dollars, or 1.1%-1.7% of initial GDP. In our model, the carbon tax generates total revenue of about 2% of initial GDP, again a similar order of magnitude.