

Carbon Pricing versus Green Finance

Lasse Heje Pedersen*

This version: November 28, 2023

Abstract

Economics recommends combating climate change with carbon pricing, but green finance (ESG investing, sustainable finance regulation) is becoming widespread. In a unified model, I show that green finance should not be used if the carbon price equals its social cost. However, with too low carbon prices, green finance can implement the social optimum if the cost of capital can be controlled and there are no stranded assets. I show explicitly how to “translate” a carbon tax into green finance terms, highlight how green finance should depend on scope 1, 2, and 3 emissions, present its limitations, and illustrate the predictions empirically.

Keywords: ESG investing, sustainable finance regulation, carbon allowances, carbon offsets, carbon credits

JEL Codes: G1, H23, E44, O44, Q5

*AQR Capital Management, Copenhagen Business School, and CEPR; e-mail: lh001@gmail.com; www.lhpetersen.com. I am grateful for helpful comments from Darrell Duffie, Niels Gormsen, Theis I. Jensen, Nicolae Garleanu, William Hogan, Markus Ibert, Claus Thustrup Kreiner, David Lando, Lukasz Pomorski, Andrei Shleifer, Aleh Tsyvinski, and seminar participants at New York University, Yale University, and Copenhagen Business School, as well as to Clara Egehoved Tørsløv for excellent research assistance. AQR Capital Management is a global investment management firm, which may or may not apply similar investment techniques or methods of analysis as described herein. The views expressed here are those of the author and not necessarily those of AQR. I gratefully acknowledge support from the Center for Big Data in Finance (Grant no. DNRF167).

Climate change is the ultimate challenge for economics according to Nordhaus (2019). In a series of papers leading to the Nobel prize, Nordhaus and others develop integrated assessment models (IAMs) that estimate the “social cost of carbon” and recommend a Pigouvian carbon tax equal to this social cost, 43 dollars per metric ton of carbon emissions (\$/tCO₂) by one estimate.

However, carbon pricing is growing slowly in the real world, while “green finance” is promoted by the UN, EU, central banks, institutional investors, and others, both in terms of “sustainable finance regulation” and investment policies based on “environmental, social, and governance” (ESG) concerns, notably the “E” part. While carbon pricing seeks to affect the *cost of emissions*, green finance seeks instead to affect the *cost of capital* of emitting firms. Using a fundamentally different mechanism to fight climate change raises several questions:

How does 43\$/tCO₂ translate into percent cost of capital? When can green finance accomplish the same as a carbon tax? What is the interaction of green finance and carbon pricing? Who should be targeted, those with direct or indirect emissions?

This paper addresses these questions by presenting a unified model of carbon pricing and green finance along with empirical evidence. In short, the model provides the following answers. First, a carbon tax of 43\$/tCO₂ translates into an increase in the cost of capital of brown energy companies using coal of 4.1% percentage points. Second, green finance can accomplish the same as a carbon tax when there are no stranded assets and the cost of capital can be fully controlled. Third, green finance and carbon pricing interact as substitutes. Fourth, green finance can be targeted at either direct or indirect emissions as long as no emissions are “missed” or “double-counted.”

The model includes green and brown energy firms, goods producers with different energy needs and pollution levels, and consumers. The firms face both a carbon tax, carbon offset markets, and green finance. So the model is more general than IAMs in terms of its multi-pronged carbon-mitigation mechanisms, but it is far simpler in other respects, thus allowing a closed-form solution. Indeed, while one of the main results of IAMs is the calculation of the “social cost of carbon,” my model takes this social cost of carbon as given for simplicity, rather than including an ecological model of carbon circulation and damages as in IAMs.

The model delivers several intuitive results that are relevant to the current debate on the efficient regulation of greenhouse gases, as summarized in Table 1. The first theoretical result is that the social optimum can be achieved when all carbon prices — carbon taxes, carbon allowance prices, and carbon offset prices — are identical and equal to the social cost of carbon (echoing results from IAMs) and when green finance is not used at the same time.

	Carbon pricing (Cost of emission)	Green finance (Cost of capital, CoC)
<u>Literature</u>		
Field	Economics	Finance
<u>Theoretical results</u>		
Optimum		
Pure carbon pricing	Tax=cost	Zero
Green finance	Tax<cost	CoC(i , actions $_i$, cost $-tax_i$)
Problems	Offsets	Stranded assets CoC unmanageable
Implementation		
Scope 1	Tax direct emissions	CoC $\uparrow$ brown energy, $\uparrow$ brown firms
Scope 2	Upstream electricity	CoC $\downarrow$ green energy, $\uparrow$ brown firms
Scope 3	Downstream emissions	CoC $\uparrow$ green energy, $\uparrow$ brown energy
<u>Empirical results</u>		
Global use	Carbon tax, 6% Allowances, 18% Offsets, 1%	ESG investing, 48% Sustainable finance regulation, 91%
Carbon price	Too low, violates LoOP	
Neither or both	Corr(Carbon price, green finance) >0 across countries	
Country variation	Wealth, democracy, knowledge, inequality(-), emissions(-), civil law	ESG: Wealth NFGS: democracy, emissions, civil law

Table 1: **Overview of Results.**

With an optimal carbon pricing, green finance is not just superfluous, it actually distorts allocations — “too many cooks.” So, with a common global carbon price, green finance should not be used.

Empirically, I find several deviations from this ideal climate regulation. First, just 6% of global emissions are subject to a carbon tax, as seen in Table 1. More broadly, less than a quarter of emissions are subject to any “carbon pricing,” including 18% from carbon allowances (a tradable right to emit within a regulated framework, as explained in the institutional overview in Section 1) and 1% from carbon offsets (paying someone else to reduce emissions or capture carbon from the air).

Second, carbon prices are generally too low and vary significantly across global carbon taxes, global carbon allowance markets, and global offset markets. Third, using novel data on voluntary carbon offset prices, I find that this market has a surprisingly large price dispersion since a ton of carbon should be a ton of carbon regardless of its source. The model predicts

that such deviations from the law of one price (LoOP) must be due to differences in quality, and I provide empirical evidence consistent with the idea that the market views certain offsets as more credible and others as more related to “greenwashing.”

Given that carbon pricing is poorly implemented and the world is turning toward green finance, I next consider whether green finance can solve climate change. The second theoretical result in Table 1 is that, if the carbon price is too low, then green finance can nevertheless implement the social optimum, under certain conditions. This may be a surprising finding since economics is focused on carbon pricing as the sole tool to achieve the social optimum.

To understand how green finance works, consider first how to translate a carbon tax of 43\$/tCO₂ to green finance in the simplest possible case. The simplest case is when all pollution comes from a brown energy sector with constant returns to scale, resulting in the following equilibrium energy price:

$$\text{energy price} = \frac{\text{CoC} + \text{depreciation}}{\text{productivity}} + \text{cost of fuel etc.} + \text{carbon tax} \times \text{fossil intensity} \quad (1)$$

Note that the energy price can be raised via a carbon tax or a higher cost of capital (CoC) of brown energy firms, and this equation enables a translation from a carbon tax to CoC. To be concrete, introducing a carbon tax of 43\$/tCO₂ for a coal-based energy company with a fossil intensity (i.e., emission) of 0.00082 tCO₂/kWh raises the energy price by 0.035\$/kWh (where “kWh” stands for kilowatt hour). Such a tax would raise the electricity price from its existing level of around 0.17\$/kWh on average in the US, 2023.

To achieve the same increase in energy prices via green finance, suppose that the baseline electricity price of 0.17 is due to 0.085 from the first term in (1) (CoC plus depreciation, scaled by productivity), 0.085 from the second term (cost of fuel etc.), and 0 from the third term (carbon tax=0), i.e., half the revenue compensates CoC and depreciation (profit margin of 0.5). Hence, to raise the energy price by 0.035, CoC must be raised such that the first term increases by 0.035/0.085=41%. If the initial CoC was 5% and depreciation is 5%, then their sum (CoC+depreciation) must be increased by (5%+5%)×0.41=4.1%. Since depreciation is given, the CoC must increase by 4.1 percentage points. Based on these ideas, the following relation captures how the cost of capital must be raised from CoC^{base} to CoC^{green finance} to

match the effect of a carbon tax:

$$\begin{aligned}\text{CoC}^{\text{green finance}} &= \text{CoC}^{\text{base}} + \frac{\text{carbon tax} \times \text{fossil intensity} \times (\text{CoC}^{\text{base}} + \text{depreciation})}{\text{profit margin} \times \text{energy price}} \quad (2) \\ &= 5\% + \frac{43 \times 0.00082 \times (5\% + 5\%)}{0.5 \times 0.17} = 5\% + 0.1 \times \text{carbon tax} = 9.1\%\end{aligned}$$

This simple equation shows that to mimic every dollar of carbon tax, the cost of capital must be raised by approximately 0.1 percentage point. Moreover, these numbers show that a large increase in the cost of capital is needed.¹

Naturally, this increase in electricity prices affects downstream goods producers, so, if this policy is effective, there is no need to also regulate other firms for their electricity use. However, if goods producers also emit carbon, then these firms must also be regulated, so I derive how to implement green finance in more general cases.

I first consider what I denote “simple green finance” in which each firm’s cost of capital depends on how sustainable its technology is. Simple green finance only works in certain cases, notable if all pollution comes from brown energy firms as discussed before. More generally, green finance can potentially improve welfare, but cannot achieve the optimum even if all firms’ cost of capital can be fully controlled. The problem is that, while simple green finance is a powerful tool to affect investment, even if it achieves an efficient allocation of capital, it cannot ensure that firms make socially efficient use of other factors, notably their own pollution and employment. Therefore, simple green finance cannot achieve the social optimum in general.

To achieve an even better outcome, green finance must be contingent on the firms’ actions. Said differently, firms must be able to commit to a low pollution and, in doing so, ensuring a low cost of capital. Green finance must also depend on the difference between the carbon tax and the social cost of capital—the lower the carbon tax, the larger the required change in cost of capital from green finance. I show that, if the cost of capital can be chosen as any function of each firm’s characteristics and actions, then the social optimum can in principle be achieved, with one exception.

The exception, as highlighted in Table 1, is that some firms have “stranded assets,” meaning that these assets should be disposed in the social optimum. While a carbon tax can push firms to dispose of stranded assets, green finance cannot. For example, if coal-driven power plants pollute so much that their carbon tax is above the value of the generated energy,

¹This calibration is explained in more detail in Section 4.3, which also presents more general calibrations.

then running the plant becomes uneconomical. But, without a carbon tax, the plant remains profitable, and while a higher cost of capital reduces the present value of these profits, green finance cannot make it economical to shut it down.

Beyond this exception, green finance faces several broader challenges. First, the functional form of the optimal green finance is generally firm-specific, in contrast to the simple idea that everyone pays a uniform carbon tax. Second, controlling the cost of capital may not be feasible, especially to the point of creating a fine-tuned incentive scheme. Indeed, the cost of capital depends on a broad group of investors and creditors with a range of preferences and limited control by regulators. Further, the calibrated magnitude of the needed adjustments to the cost of capital appears larger than the current green-finance effects in real markets ([Berk and van Binsbergen, 2023](#); [Eskildsen et al., 2023](#)). Indeed, while 4.1% is already a very large increase in cost of capital, the effect should be five times larger over time, since the social cost of capital is five times larger over time ([Nordhaus, 2019](#)).

Nevertheless, I find that green finance is becoming prevalent is seen in Table 1. Indeed, 91% of countries have a regulator who is a member of The Network of Central Banks and Supervisors for Greening the Financial System (NGFS), as a fraction of global GDP. Further, the collective assets under management (AUM) of all signatories of the Principles of Responsible Investment is 48% of the combined market value of global equity markets and global fixed income markets. So, at least in terms of stated intentions, green finance is extremely widespread. Similarly in academia, the ESG literature may be taking center stage despite its abstraction from carbon taxes.² But green finance still has limited effect, so the disconnect between the widespread intentions and the limited effect highlights a challenge of green finance.

Given that green finance and carbon pricing are substitutes, it is interesting to consider empirically whether countries tend to have either mechanism or both. In fact, looking across countries, carbon pricing is positively linked to green finance — both to ESG investing and to sustainable finance regulation. In other words, some countries have several tools while other countries have none. One potential explanation could be that some countries try to regulate domestic emissions via taxes, but as foreign emissions cannot be taxed, local investors may instead turn to ESG investing in global markets.

²For example, the [Nobel Committee \(2018\)](#) emphasizes the contribution of [Nordhaus \(1994\)](#), which has 2,256 Google Scholar citations as of this writing. This number is surpassed by ESG papers such as [Hong and Kacperczyk \(2009\)](#) with 2,496 Google Scholar citations despite ESG being a newer literature, and even recent ESG papers such as [Berg et al. \(2022\)](#) already has 984, [Pástor et al. \(2021\)](#) and [Pedersen et al. \(2021\)](#) each have around 600, and [Flammer \(2013\)](#) has 1,440.

Another issue from Table 1 that is heavily debated among regulators and practitioners is whether a firm's carbon emissions should be assessed as its direct emission (so-called "scope 1" emission) or also include indirect emissions coming from its energy use ("scope 2") or all indirect upstream and downstream emissions in the supply chain ("scope 3"). While many argue that scope 2 or 3 are preferred as being more comprehensive, the model shows that the social optimum can be achieved using any scope of emissions, as long as the policy does not miss or double-count any emissions. This is true both for carbon pricing and green finance, but I focus here in the more novel case of green finance.

A scope-1 approach to green finance has the following three elements: (a) vastly increase the cost of capital for brown energy due to their high direct emissions; (b) leave the cost of capital unchanged for green energy with no emissions; and (c) modestly increase the cost of capital for other types of firms with modest direct emissions. This approach works in part by increasing energy prices due to the high cost of capital for brown energy, thus incentivizing investment in green energy and a reduced energy consumption more broadly.

A scope-2 approach is to (a) leave the cost of capital for brown electricity unchanged; (b) increase instead the cost of capital for firms that buy electricity and firms that pollute themselves; and (c) highly subsidize the cost of capital for green energy since this approach does not increase energy prices.

Finally, a scope-3 approach is to (a) vastly increase the cost of capital of brown energy companies to reflect both their own emissions in the downstream emissions of the firms that buy the energy; (b) leave the cost of capital for goods producers unchanged; and (c) slightly increase the cost of capital for green energy to reflect the emissions of downstream buyers of the energy.

In sum, there are several different ways to implement green finance, and a broader scope is not always better. So why are regulators and investors focused on scope 2 or 3? One reason could be that green investors only have a small effect on the cost of capital (Berk and van Binsbergen, 2023), so, when optimal green finance is infeasible, green investors might simply seek a small effect in as many places as possible, slightly increasing the cost of capital for brown firms while slightly lowering the cost of capital for green firms.

I end by studying the links between societal conditions across countries and, respectively, carbon pricing and green finance. I find a positive link between a country's carbon price and its wealth, level of democracy, knowledge of climate change, civil law, and a negative relation to income inequality, and emissions per capita in 2000, as seen in Table 1. Similarly, ESG investing across countries is positively linked to the wealth of the country while sustainable

finance regulation is linked to democracy and emissions.

The paper is related to two distinct literatures: (i) the economics literature on carbon pricing and (ii) the finance literature on ESG investing and sustainable finance regulation. Sections 1.1 and 1.2 review these literatures, respectively, and provide institutional details. To the best of my knowledge, this paper is the first to combine the environmental approaches of these two literatures in a unified “workhorse model.” While IAMs only include a carbon tax, I also include two market-based alternatives, carbon offsets and green finance.

What new results arise from combining these literatures? Clearly, the economics literature, e.g., Nordhaus (1994), already shows that a carbon tax can implement the optimal solution, and, in this connection, I add the fairly obvious point that not only is green finance not needed, it would actually be harmful with full carbon pricing. More substantially, while there is public finance research on second-best outcomes with abstract forms of “imperfect instruments,” I study the empirically relevant alternative, green finance, and provide conditions under which it can implement the first-best solution.³ I also present the limitations of green finance due to stranded assets and to problems with managing the cost of capital of the magnitude that I calibrate. I show how to map a carbon tax, say 43\$/tCO₂, into green-finance terms, and how this mapping depends on carbon prices and who is regulated (the scope). Lastly, I present empirical evidence of the global coverage of these mechanism, their links to societal conditions, and the market for carbon offsets.

1 Understanding Carbon Pricing and Green Finance

This section provides a brief overview of the literature and the real-world institutional arrangement for fighting climate change before turning to the theoretical and the empirical results in the sections to follow.

1.1 Carbon Pricing

IAMs for carbon pricing at the social cost of carbon are developed in a string of papers by Nordhaus, Peck and Teisberg (1992), Golosov et al. (2014), Daniel et al. (2019), and other papers surveyed in Nobel Committee (2018).

³While a carbon tax is the standard Pigouvian solution to an externality, ESG investing and sustainable finance regulation can be viewed as examples of imperfect instruments. Imperfect instruments are discussed in Diamond (1973), Dávila and Walther (2022), and references therein, but, to my knowledge, the focus on instruments that work via the cost of capital is new.

There is evidence that carbon taxes work, including [Andersson \(2019\)](#) who empirically finds “a significant causal effect of carbon taxes on emissions” in Sweden. In contrast for carbon offsets, [Calel et al. \(2021\)](#) estimate for wind farms in India “that at least 52% of approved carbon offsets were allocated to projects that would very likely have been built anyway. In addition to wasting scarce resources, we estimate that the sale of these offsets to regulated polluters has substantially increased global carbon dioxide emissions.”⁴ While the literature focuses on offset quantities in a specific market, my novel data on offset prices illustrates the lack of credibility of this market more broadly.

Carbon Allowances and Carbon Taxes

As of 2022, 37 states or regions have carbon taxes globally ([The World Bank, 2022](#)). The implementation of carbon taxes varies across regions in terms of the price of emitting carbon, disclosures of future prices, the sectors covered, possible exceptions (often related to competitiveness), the scope of regulation, and the “point of regulation” (i.e., who pays the tax). The point of regulation can be (i) at the source, that is, the firms actually emitting carbon, e.g. by burning fossil fuels; (ii) upstream, that is, producers, distributors, and importers of the fossil fuels; and/or (iii) downstream, e.g., firms using energy produced with emissions.

Another way to price carbon is via an emissions trading system (ETS). As of 2022, 34 states or regions have ETSs globally, and a total of 68 regions have either carbon taxes, an ETS, or both ([The World Bank, 2022](#)). Introducing an ETS means that the government places a cap on total emissions in certain sectors of the economy, and then auctions or distributes tradable emission allowances to entities covered by the cap. This system is known as a “cap-and-trade,” or “baseline-and-credit” if firms are allowed a baseline emission and can sell credits if they reduce emissions below the baseline. Each carbon allowance typically represents the permission to emit one metric ton of CO₂. Allowances can be traded until they are finally “surrendered” for the appropriate year to the regulator.

Carbon Offsets

A carbon offset is a financial instrument that, in principle, represents one metric ton of carbon dioxide equivalent avoided or removed from the atmosphere. Whether the offset

⁴Also, [Känzig \(2022\)](#) finds that a price increase in the European ETS leads to a significant fall in emissions at the cost of a temporary fall in economic activity, born mostly by poorer households. [Kaplan et al. \(2023\)](#) propose an auditable framework for offset accounting.

truly accomplishes this goal^æ is debated, and people look for five quality attributes: The offset should be real, additional, verifiable, enforceable, and permanent.

Some carbon offsets are part of a regulatory framework such as the Kyoto Protocol (e.g., the Clean Development Mechanism studied by [Calel et al. \(2021\)](#)), Paris Agreement, or regional carbon pricing initiatives (e.g., the California Compliance Offset Program and the Australia Emissions Reduction Fund).

There is also a rising market for voluntary carbon offsets, where firms buy offsets without a regulatory reason. Such offsets are generated via an extensive process, starting with a “methodology” that specifies to the type of offset project generating the reductions. Then the project is developed, validated by an independent “verifier,” and registered on a carbon offset “registry.” The offsets can then be traded (often via various brokers), transferring the offset into the buyer’s name at the registry, and is ultimately “retired.” That is, a holder of offsets must retire the offset in order to claim their associated carbon reductions and, once retired, the offset can no longer be transferred. Carbon offsets are characterized by the amount of carbon (or, more precisely, the CO₂-equivalent greenhouse gas reductions), the project, the registry, verifier, and “vintage,” meaning the year in which the carbon reduction takes place. Offsets can be traded before and after the vintage year (as long as they are not retired).

Connection Between Allowances and Offsets

In some regulatory frameworks, certain carbon offsets can be used to comply with the carbon regulation (sometimes with a limit on the number of offsets that can be used). In such cases, the carbon offset reduces the burden to acquire allowances, thus presenting an alternative method of compliance.

Vice versa in the voluntary carbon markets, firms can, in some cases, buy and cancel carbon allowances from compliance markets as an alternative to buying voluntary offsets, thus reducing the available allowances in a cap-and-trade system. In other words, the idea is to reduce the total permitted emissions by regulated entities, thus tightening the cap.

Carbon Futures Markets

Carbon is also traded in futures markets. Notably, the Intercontinental Exchange (ICE) has futures contracts on the four most actively traded carbon allowance markets (ETSs) in the world, the European Union ETS, the Western Climate Initiative (California Cap and Trade

Program), the Regional Greenhouse Gas Initiative (RGGI), and the UK ETS.⁵ Also, the Chicago Mercantile Exchange (CME) has a “CBL Global Emissions Offset” (GEO) futures, which provides “delivery of physical carbon offset credits that have undergone stringent screening.”⁶

1.2 Green Finance

Sustainable Finance Regulation

Many investors and regulators are interested in complementing the regulation of carbon pricing with other tools. For example, the Network for Greening the Financial System is an extensive group of central banks and financial supervisors who aim to “help strengthening the global response required to meet the goals of the Paris agreement and to enhance the role of the financial system to manage risks and to mobilize capital for green and low-carbon investments in the broader context of environmentally sustainable development.”⁷ Also, the European Banking Authority is rolling out an effort “to integrate ESG risks considerations in the banking framework and support the EUs efforts to achieve the transition to a more sustainable economy.”⁸ This regulation may be targeting firms’ direct emissions (scope 1) or also their indirect emissions (scope 2 and 3). There is limited academic work on sustainable finance regulation, but climate stress testing is starting to receive attention (Acharya et al., 2023, and references therein), which can influence bank’s capital requirements and in turn their creditors’ cost of capital.

ESG Investing

At the same time, many investors are including environmental, social, and governance (ESG) criteria in their investment decisions. For example, 4,902 institutional investors “with an estimated total of AUM of US\$121.3 trillion” have signed the Principles for Responsible Investments, an organization furthering ESG investing supported by the United Nations (PRI Annual Report, 2021-2022). Likewise, a number of sustainable investment products for retail investors are gathering interest (and regulation). Some investors may even buy carbon offsets against the emissions of the firms held via financial securities (Alankar and Scholes, 2022).

⁵See www.ice.com/fixed-income-data-services/index-solutions/commodity-indices/carbon-futures.

⁶See www.cmegroup.com/markets/energy/emissions/cbl-global-emissions-offset.html.

⁷See <https://www.ngfs.net/en>.

⁸See, e.g., <https://www.eba.europa.eu/eba-publishes-its-roadmap-sustainable-finance>.

These investor preferences can raise the required returns for brown firms relative to the required returns of green firms (Pástor et al. (2021) and Pedersen et al. (2021)), affect the choice of capital structure (Feldhütter and Pedersen, 2022), and improve welfare (Hong et al., 2021). Empirical evidence that ESG investing affects the costs of capital is provided for stocks by Hong and Kacperczyk (2009) and Bolton and Kacperczyk (2021), for corporate managers' perceived costs of capital by Gormsen et al. (2023), and for bonds by Flammer (2021), Baker et al. (2022), and Feldhütter and Pedersen (2022). Whether ESG investing can matter enough to affect firm behavior has been questioned (Berk and van Binsbergen, 2023), may be neutral (Arnold, 2023), or even counterproductive (Hartzmark and Shue, 2023).

My model derives new results by unifying this literature with the carbon pricing literature, and it can also be applied to other elements of ESG investing. For example, investors concerned with the social element (the “S” in ESG) may disinvest from alcohol or tobacco firms to raise their cost of capital. As with carbon, it is interesting to contrast this ESG approach with a Pigouvian tax. Indeed, such firms with social issues can also be regulated more directly via alcohol and tobacco taxes.

2 A Model of Carbon Pricing and Green Finance

As seen in Figure 1, the economy consists of firms producing consumption goods with varying degrees of carbon emissions; green and brown energy producers; producers of carbon offsets; households who invest, work, and consume; and a government. The model has two time periods: At time 0, firms make real investments using capital raised from households and intermediated by banks and investment funds subject to green finance. At time 1, firms produce and emit carbon while households work and consume. The model is intended to have all these elements in the simplest possible way.

Firms Producing Consumption Goods

The economy has N price-taking firms producing consumption goods, indexed $i = 1, \dots, N$. At time 0, each firm chooses its capital, K_i , and, at time 1, the firm produces its output using the capital, its chosen labor workforce, L_i , and its endogenous energy intensity, ϵ_i , via the production function:

$$Y_i = a_i \epsilon_i^{s_i} L_i^{\beta_i} K_i^{\alpha_i} \quad (3)$$

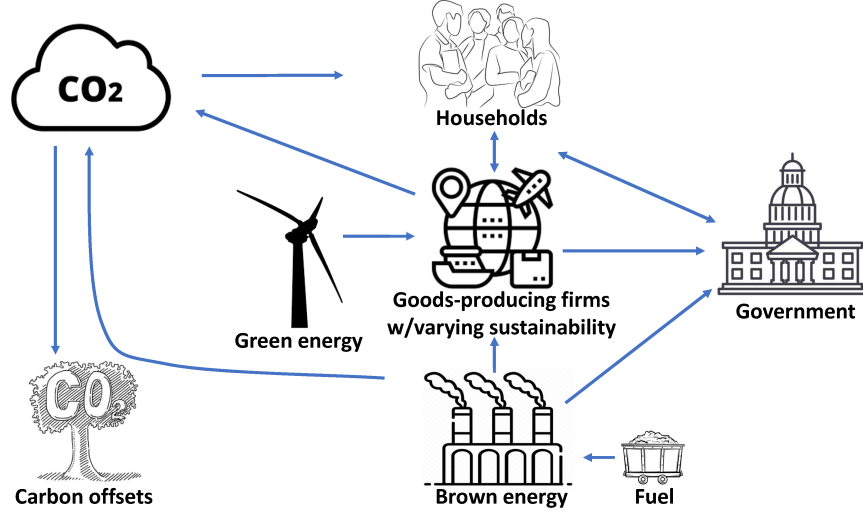


Figure 1: Model Overview

Here, $a_i > 0$ is a productivity parameter, $s_i \in (0, 1)$ is a parameter that captures sustainability problems, and $\alpha_i + \beta_i < 1$ are standard production parameters.

The energy intensity, $\epsilon_i = \text{ENERGY}_i/Y_i$, is the firm's energy use as a fraction of total output.⁹ Choosing a higher energy intensity makes the firm more productive as seen in (3), which creates a tradeoff of productivity against the environmental costs of energy. This tradeoff is more severe for firms with higher sustainability issues, s_i , since the productivity of such firms is highly dependent on ϵ_i .

Using energy has two costs. The first cost is the price of buying energy, p_i , for example the cost of electricity, heating oil, or gasoline for company cars. The energy cost may depend on how much green versus brown energy the firm buys, $p_i = p_b\lambda_i + p_g(1 - \lambda_i)$, where λ_i is the proportion of brown energy, and p_g and p_b are the prices of green and brown energy, respectively. The firm's expenditure on energy service is therefore $p_i\text{ENERGY}_i = p_i\epsilon_i Y_i$.

The second cost of using energy is the potential carbon tax it creates. The carbon tax works as follows. The firm's energy use results in scope-1 CO2 emissions (i.e., its own direct emissions) of

$$\text{CO2}_i^{\text{Scope-1}} = f_i^1 \text{ENERGY}_i = f_i^1 \epsilon_i Y_i \quad (4)$$

⁹While focusing on energy intensity ϵ_i is consistent with practice among ESG investors and sustainable finance regulation, the production function can be rewritten as a function of ENERGY, $Y_i = a_i^{\frac{1}{1+s_i}} \text{ENERGY}_i^{\frac{s_i}{1+s_i}} L_i^{\frac{\beta_i}{1+s_i}} K_i^{\frac{\alpha_i}{1+s_i}}$, which clarifies that its specification is similar to that of the DICE model proposed by Nordhaus (1992), see also the overview in Nobel Committee (2018).

where $f_i^1 \geq 0$ is the scope-1 “fossil intensity” (emission per energy use). Hence, $f_i^1 \epsilon_i$ is the so-called “carbon intensity” (CO2 emission per unit of output). To understand the units of account, think of ENERGY_i as measured in kilowatt-hours (kWh), $\text{CO2}_i^{\text{scope-1}}$ as measured in metric tons of carbon-dioxide-equivalent emissions (tCO2e), f_i^1 as measured in tCO2/kWh, Y_i as measured in dollars (\$), and ϵ_i as measured in kWh/\$ dollars.

The firm also has indirect emissions stemming from its energy suppliers, so its scope-2 (and scope-3) emissions can be larger than scope-1. The amount of scope-2 emission is $\text{CO2}_i^{\text{scope-2}} = f_i^2 \epsilon_i Y_i$, where the scope-2 fossil intensity is $f_i^2 = f_i^1 + \lambda_i F^1$, F^1 is the scope-1 fossil intensity of the brown energy firm, and λ_i is the proportion of brown energy. The scope-3 emission is the scope-2 emission plus any emissions at the consumer level, which are set to zero for simplicity (although the model easily extends to such consumer emissions).

The firm pays a “carbon tax,” $\tau_i f_i \epsilon_i Y_i$, where τ_i is the price per emission and f_i equals f_i^1 or f_i^2 depending on the scope of regulation. This carbon tax can be interpreted as an actual tax, the price of CO2 allowances (modelled more explicitly in Appendix A), or the cost of emitting due to negative reactions from customers or other stake holders (see Section 1 for institutional details).

The firm can reduce this carbon tax by buying carbon offsets of various qualities, $(o_{i,q})_{q \in [0,1]}$, where $o_{i,q}$ is the number of offsets of quality q bought by firm i . The price of an offset of quality q is given by the endogenous price ϕ_q . The firm faces a net carbon tax that depends on its emission less its allowed offsets, $\tau_i (f_i \epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_q)^+$, where $\bar{q}_i$ is the minimal allowed quality for this firm (and the superscript “+” indicates that the tax can never be negative).

The firm’s profit, Π_i , at time 1 is given by its output less labor costs at wage w , energy costs, carbon taxes, and offset costs:

$$\Pi_i = Y_i - wL_i - p_i \epsilon_i Y_i - \tau_i (f_i \epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_{i,q})^+ - \sum_q o_{i,q} \phi_q \quad (5)$$

This profit is paid to the firm’s owners at time 1. The firm’s capital, K_i , comes from its real investment, $I_i = K_i$, which is made at time 0. The firm maximizes its net present value,

$$NPV_i = \frac{\Pi_i + (1 - \delta)K_i}{1 + r_i} - K_i = \frac{\Pi_i - (r_i + \delta)K_i}{1 + r_i}, \quad (6)$$

based on a cost of capital of r_i and depreciation, δ . This cost of capital is set by the owners who infuse the capital, and it can depend on green-finance considerations as discussed further below.

In summary, the firm chooses at capital (K_i) at time 0 and its labor, energy, and offsets ($L_i, \epsilon_i, \lambda_i, o_{i,q}$) at time 1 in order to maximize NPV.

Production of Energy Service: Brown and Green Energy

The economy has two technologies for energy, brown and green. Brown energy is based on fossil fuels. The representative brown energy firm has an existing capital of $\bar{K}_b$, which it can decide to use or dispose, and it makes an additional investment of $I_b \geq 0$. This brown capital yields a production of energy of $x_b = a_b(\bar{K}_b 1_{\{\text{use}\}} + I_b)$, using x_b units of fuel, where a_b is productivity. The firm buys the fuel for π and sells the energy (electricity) for p_b per unit of output. This brown energy production creates a direct CO2 emission of $F^1 x_b$. The resulting carbon tax in dollars is $\tau_b(F_b x_b - o_b)$, where τ_b is the carbon price per emission, o_b is offsets purchased (assumed to be of quality 1, for simplicity), and F_b is the regulated fossil intensity, which depends on the scope of regulation. In particular, $F_b = F^1$ based on scope-1 or scope-2 regulation, and $F_b = F^1 + f_i^1$ based on scope-3 regulation, which includes the emission of the firm buying the energy. The brown capital depreciates at a rate of δ_b and the brown energy firm maximizes its NPV based on a cost of capital of r_b .

The green energy company invests in a wind (or solar) farm with $I_g = K_g$ turbines at time 0. The green investment comes with an adjustment cost of $\frac{\xi}{2}(I_g)^2$, where $\xi > 1$, which captures the idea that switching to green energy is costly in the short term. The green investment yields an energy production of $a_g K_g$ with no emissions. The firm can sell this energy for $p_g a_g K_g$ at time 1, where p_g is the price of green energy, which can differ from the price of brown energy, p_b , if firms face a scope-2 carbon tax. The green energy company has regulated emission of $F_g a_g K_g$, where the scope-1 and scope-2 emissions are zero ($F_g = 0$) while scope-3 emissions take into account the emission of goods producers ($F_g = f_i^1$), and the carbon price per emission is τ_g net of offsets, o_g . The green company maximizes its net present value with a cost of capital of r_g and a depreciation of δ_g .

Production of Fuel and Offsets

The representative coal mining firm (or oil drilling firm) can produce x_b units of fuel for ρx . With a competitive mining industry, the equilibrium fuel price is $\pi = \rho$, and I simply use the notation π from now on.

A representative producer of offsets can produce offsets of quality q for each quality $q \in [0, 1]$. A quality of $q = 1$ means that the producer reduces carbon one-for-one with

the number of offsets sold, e.g. via carbon capture. A lower quality means that the carbon reduction is expected to be less than the claimed amount. Specifically, the quality q indicates the ratio of the actual expected carbon reduction to the claimed amount.

Offset producer q can produce o_q offsets at a the cost of $o_q\mu_q$, i.e., a constant marginal cost of μ_q . Producers with higher quality face higher marginal costs, which is an assumption without loss of generality since, if producers with higher costs and lower quality existed, then these “dominated” producers would deliver zero offsets in equilibrium anyway. Further, since a package of $1/q$ offsets of quality q can be sold as a single offset of quality 1, it holds that $\mu_q/q \geq \mu_1$ for all $q \in (0, 1)$. In a competitive equilibrium, the price of carbon offsets equal their marginal costs, $\phi_q = \mu_q$ for all q .

Investment and Green Finance

At time 0, the representative household is endowed with a wealth of W and ownership of all firms and all producers of energy and offsets. The household can transfer wealth into the future with a risk-free return of r , yielding rW . The household can also provide some of the wealth as investment capital I_i to any firm i , yielding a profit from production, of Π_i . Hence, the competitive cost of capital is r , meaning that investing in firm i is profitable if and only if $\frac{\Pi_i + (1-\delta)K_i}{1+r} - I_i \geq 0$.

However, investors are not just motivated by these financial considerations, they may require another rate of return $r_i \neq r$ for any firm i due to their environmental, social, and governance (ESG) considerations or due to sustainable finance regulation. The green finance considerations may operate via banks, asset managers, or other intermediaries, as explained in Section 1.2. In other words, the firm maximizes $NPV_i = \frac{\Pi_i + (1-\delta)K_i}{1+r_i} - I_i$, which can be interpreted at the stock price at time 0.

It is interesting to consider two types of green finance: (i) simple green finance and (ii) green finance with commitment. Here, (i) means that the cost of capital r_i is allowed to differ across firms, depending on their sustainability parameter s_i and other firm characteristics, but, once the firm has received its financing at time 0, it can freely chose its energy intensity and its other actions at time 1.

In contrast, (ii) means that the firm can commit to its actions at time 1 and the cost of capital at time 0 then depends on these actions. For example, the cost of capital can depend on the future choice of energy intensity, $r_i(\epsilon_i)$. This type of green finance captures the idea that, in a multi-period world, the firm can be punished for past pollution or gain a

reputation for being green.

Consumption, Pollution, and Welfare

After the representative household has made its investments in time 0, then at time 1, the household works and consumes. The household earns an endogenous wage, w , by supplying any amount of labor L at a marginal cost of $\bar{w}$, subject to a proportional income tax with tax rate τ_w . The household's overall utility is its consumption, C , less its disutility of work, $\sum_i \bar{w}L_i$, and less its disutility of carbon emissions:

$$U = C - \sum_i \bar{w}L_i - T \left(\sum_i f_i^1 \epsilon_i Y_i + F^1 x_b - \sum_{i,q} q o_{i,q} - o_b - o_g \right)^+ \quad (7)$$

The last term is the social cost of carbon, T , times total emissions, which is emissions from firms (the scope-1 fossil intensity times their energy use), plus emissions from brown energy producers, less offsets. The first term in (7) is the household's consumption, C ,

$$C = (1+r)(W - \sum_i I_i - I_b - I_g) + \sum_i (\Pi_i + (1 - \tau_w)wL_i) + \Pi_b + \Pi_g + K' + G \quad (8)$$

which is the sum of all its sources of income. The income comes from savings, $r(W - \sum_i I_i - I_b - I_g)$, firm profits, $\sum_i \Pi_i$, after-tax labor income, $(1 - \tau_w)w \sum_i L_i$, profit from brown energy producers, $\Pi_b = (p_b - \pi)x_b - \tau_b(Fx_b - o_b) - o_b\phi_1$, profit from green energy firms, $\Pi_g = p_g a_g K_g - \frac{\xi}{2} K_g^2 - \tau_g(F_g a_g K_g - o_g)$, final capital, $K' = (1 - \delta) \sum_i K_i + (1 - \delta_b)K_b + (1 - \delta_g)K_g$, and government spending, $G = \sum_i \tau_i(f_i \epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_{i,q})^+ + \tau_b(Fx_b - o_b) + \tau_g(F_g a_g K_g - o_g) + \sum_i \tau_w w L_i$, which equals income from carbon taxes and income taxes, thus balancing the government's budget.

3 Equilibrium: Closed-Form Solution

A competitive equilibrium is a wage, w , and prices green and brown energy, p_g, p_b , such that the labor market and energy markets clear when each goods producer chooses $(\epsilon_i, \lambda_i, o_{iq}, L_i, K_i)$ to maximize their value, energy producers maximize profits, and workers supply labor to maximize their utility.

3.1 Carbon Offset Markets and the Effective Carbon Price

The market for offsets is very simple. Firms of different types (characterized by their parameters, $a_i, s_i, \alpha_i, \beta_i, \tau_i, \bar{q}_i$) buy offsets from different offset producers (characterized by their parameters, q, ϕ_q).

If firm i buys any offsets, then the firm buys offsets of the minimum quality $\bar{q}_i$ allowed since the price of offsets is increasing in quality q . Buying these cheapest-allowed offsets costs $\phi_{\bar{q}_i}$, so this is economical if the cost is lower than the carbon tax that is saved, $\phi_{\bar{q}_i} \leq \tau_i$. If so, the firm buys enough of these offsets to cover their entire carbon emission and is then able to state that it is “carbon neutral.” Otherwise, if $\phi_{\bar{q}_i} > \tau_i$, it is cheaper to pay the carbon tax, and the firm buys zero offsets.

Therefore, each firm i faces an “effective carbon price” of

$$\tilde{\tau}_i = \min\{\tau_i, \phi_{\bar{q}_i}\} \quad (9)$$

Similarly, green and brown energy companies face effective carbon prices of $\tilde{\tau}_g$ and $\tilde{\tau}_b$, respectively.

3.2 Total Energy Cost and Equilibrium Energy Intensity

Firm i has a “total energy cost,” $\bar{p}_i$, equal to the energy purchase price, p_i , plus the effective carbon price from (9) times the regulated fossil intensity, f_i ,

$$\bar{p}_i = p_i + \tilde{\tau}_i f_i \quad (10)$$

Working with this total energy cost simplifies model substantially, starting with firm profits:

$$\Pi_i = Y_i - wL_i - \bar{p}_i \epsilon_i Y_i = Y_i(1 - \bar{p}_i \epsilon_i) - wL_i = a_i \epsilon_i^{s_i} (1 - \bar{p}_i \epsilon_i) L_i^{\beta_i} K_i^{\alpha_i} - wL_i \quad (11)$$

The profit-maximizing energy intensity therefore maximizes $\epsilon_i^{s_i} (1 - \bar{p}_i \epsilon_i)$, which yields the first-order condition $0 = s_i \epsilon_i^{s_i-1} - \bar{p}_i (s_i + 1) \epsilon_i^{s_i}$, with solution given by

$$\epsilon_i = \frac{s_i}{1 + s_i} \frac{1}{\bar{p}_i} \quad (12)$$

Naturally, the firm’s energy intensity decreases in the total energy cost, $\bar{p}_i$, and increases in the firm’s sustainability problems, s_i . With this choice of energy intensity, the firm’s profit

becomes the standard formula that only depends on the labor and capital:

$$\Pi_i = A_i L_i^{\beta_i} K_i^{\alpha_i} - w L_i \quad (13)$$

where the “productivity” based on the chosen energy intensity is

$$A_i = a_i \left(\frac{s_i}{1 + s_i \bar{p}_i} \right)^{s_i} \frac{1}{1 + s_i}. \quad (14)$$

3.3 Equilibrium in the Labor and Capital Markets

The labor choice that maximizes the profit (13) is

$$L_i = \left(\frac{\beta_i A_i K_i^{\alpha_i}}{w} \right)^{\frac{1}{1-\beta_i}} \quad (15)$$

Given the household’s cost of labor supply, $\bar{w}$, and income tax, τ_w , the equilibrium wage must satisfy $(1 - \tau_w)w = \bar{w}$, that is, $w = \frac{\bar{w}}{1-\tau_w}$.

Consider next the firm’s choice of real investment given its cost of capital, r_i . The firm chooses investment, $I_i = K_i$, to maximize its net present value given by (6). The firm’s profit Π_i depends on K_i in a way that can be determined by inserting the optimal choices of energy intensity, offsets, and labor into (13):

$$\Pi_i = A_i^{\frac{1}{1-\beta_i}} K_i^{\frac{\alpha_i}{1-\beta_i}} w^{-\frac{\beta_i}{1-\beta_i}} \beta_i^{\frac{\beta_i}{1-\beta_i}} (1 - \beta_i) \quad (16)$$

Using this profit relation, the first order condition for the choice of capital in the NPV equation (6) yields the optimal investment policy:

$$K_i = \left((r_i + \delta)^{-1} A_i^{\frac{1}{1-\beta_i}} w^{-\frac{\beta_i}{1-\beta_i}} \beta_i^{\frac{\beta_i}{1-\beta_i}} \alpha_i \right)^{\frac{1-\beta_i}{1-\alpha_i-\beta_i}} \quad (17)$$

This relation treats r_i as a fixed number, consistent with competitive markets or the planner’s problem ($r_i = r$) and with simple green finance. However, under green finance with commitment, r_i depends on all the firm’s actions, so the whole derivation of equilibrium becomes more complex. For brevity, the derivations of results with commitment are relegated to the proofs.

3.4 Equilibrium in the Markets for Green and Brown Energy

If goods-producing firms are taxed on scope-1 emissions, then their choice of green versus brown energy does not affect their carbon tax. Hence, in this case, the price of green and brown energy is the same, $p_g = p_b$.

If instead firms are taxed based on their scope-2 or scope-3 emissions, then their choice of energy source affects their carbon tax. In this case, green energy is more expensive than brown energy in equilibrium. Any firm i with an effective carbon price of $\tilde{\tau}_i$ optimally chooses its proportion of brown energy λ_i to minimize its total cost of energy:

$$\begin{aligned}\bar{p}_i &= p_i + \tilde{\tau}_i f_i \\ &= (\lambda_i p_b + (1 - \lambda_i) p_g) + \tilde{\tau}_i (f_i^1 + \lambda_i F^1) \\ &= p_g + \tilde{\tau}_i f_i^1 + \lambda_i (\tilde{\tau}_i F^1 - [p_g - p_b])\end{aligned}\tag{18}$$

So, naturally, firms that face a low carbon tax ($\tilde{\tau}_i F^1 < p_g - p_b$) choose to only buy brown energy ($\lambda_i = 1$) while firms that face a high carbon tax ($\tilde{\tau}_i F^1 > p_g - p_b$) choose to only buy green energy ($\lambda_i = 0$). In equilibrium, the demand for green energy must equal the supply of green energy, and the marginal firm with a tax of $\tilde{\tau}$ must be indifferent between green and brown energy, leading green prices to be higher than brown:

$$p_g = p_b + \tilde{\tau} F^1 1_{\{\text{Firms face scope-2 or scope-3 carbon tax}\}}\tag{19}$$

where the indicator is used so that (19) holds in all cases.

To determine the level of energy prices, consider first the green energy company's investment in wind turbines, K_g , which solves

$$\max_{K_g} \frac{p_g a_g K_g - \tilde{\tau}_g F_g a_g K_g + (1 - \delta_g) K_g - \frac{\xi}{2} K_g^2}{1 + r_g} - K_g\tag{20}$$

given the energy green price, p_g , the cost of capital, r_g , the adjustment cost, $\frac{\xi}{2} K_g^2$, and the potential scope-3 carbon tax, $\tilde{\tau}_g F_g$. The solution is $K_g = \frac{1}{\xi} ((p_g - \tilde{\tau}_g F_g) a_g - (r_g + \delta_b))$.

Consider next the brown energy company's investment, I_b , which determines its capital, $K_b = I_b + \bar{K}_b$, together with the existing capital, $\bar{K}_b$:

$$\max_{I_b \geq 0, \text{use} \in \{0,1\}} \frac{(p_b - \pi - \tilde{\tau}_b F_b) a_b (I_b + \bar{K}_b 1_{\{\text{use}\}}) + (1 - \delta_b) (I_b + \bar{K}_b)}{1 + r_b} - I_b\tag{21}$$

Given the constant returns to scale, there are four possible outcomes depending on the magnitude of the profitability, $(p_b - \pi - \tilde{\tau}_b F_b)a_b - (r_b + \delta_b)$. First, if this profitability is greater than zero, the brown firm invests infinitely, so this cannot happen in equilibrium.

Second, if profitability is zero, the brown firm makes any investment that clears the energy market. In this case, the energy price is the sum of the user cost of capital adjusted for productivity, $\frac{r_b + \delta_b}{a_b}$, the fuel cost, π , and the carbon tax, $\tilde{\tau}_b F_b$

$$p_b = \frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F_b. \quad (22)$$

as stated in (1) in the introduction.

Third, if profitability is negative, the firm makes zero investment, $I_b = 0$. Fourth, if the price is so low that $p_b < \pi + \tilde{\tau}_b F_b$, then the brown energy firm even disposes of its existing capital, $\text{use} = 0$, and produces nothing.

Market clearing for energy requires that

$$\sum_i \epsilon_i Y_i = a_g K_g + a_b (I_b + \bar{K}_b 1_{\{p_b \geq \pi + \tilde{\tau}_b F_b\}}) \quad (23)$$

The demand for energy (the left-hand side) is strictly decreasing in the price p_b , and the supply (the right-hand side) is increasing in p_b , yielding a unique equilibrium. If the energy market clears at a low energy price, $p_b < \frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F_b$, then the brown energy company does not invest $I_b = 0$, and demand for energy is met by green energy plus potential brown energy from existing assets. If energy demand exceeds supply for all prices $p_b < \frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F_b$, then $p_b = \frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F_b$ and the brown energy company clears the market.

4 Theoretical Results

4.1 Optimality of Carbon Pricing versus Green Finance

To study whether the market reaches the social optimum, the competitive equilibrium must be compared to the socially optimal “planner’s problem” of maximizing utility (7). To solve the planner’s problem, note first that, if offset costs are above the externality cost, $\phi_1 \geq T$, then offsets are not socially useful, and otherwise all emissions should be offset. As a result,

the planner's effective social cost of carbon is

$$\tilde{T} = \min\{T, \phi_1\} \quad (24)$$

The following result shows how to achieve the social optimum using the standard mechanism from economics, namely carbon pricing. All proofs are in the appendix.

Proposition 1 (Carbon Pricing with No Green Finance) *The market equilibrium is socially optimal when each firm faces the same carbon tax levied on their scope 1 emissions equal to the social cost of carbon, T , all firms are required to buy high-quality offsets, $\bar{q}_i = 1$, no green finance ($r_i = r$), and $\tau_w = 0$. In such a socially optimal equilibrium, all offsets with positive trading volume have the same price.*

As is well-known from economics, when the externality, carbon emission, is taxed at its social cost, the market equilibrium reduces global emissions in a socially optimal way. The new part of the proposition is the obvious addendum, that with such an optimal carbon tax, there is no need for green finance (i.e., $r_i = r$ for all i). In fact, green finance distorts the equilibrium if carbon is already being taxed.

Further, the optimal policy has the property that all carbon offsets should have the same price because a ton of carbon is a ton of carbon. In other words, any price differences reflect poor quality (greenwashing), which creates distortions. To see why, suppose for example that some carbon offsets only reduce emissions by 10% of their claimed effect. Why is this a problem if such offsets only trade at a “fair” price of 10% of that of fully credible offsets? The problem is that, if firms can buy such offsets to reduce their carbon tax one-for-one, then the firm's carbon tax is essentially reduced to 10% of the intended level, thus distorting the firm's incentive to reduce emissions.

As mentioned earlier, Proposition 1 shows that, if carbon is taxed at its social cost, then green finance distorts the equilibrium. As the saying goes “too many cooks spoil the broth,” so if the “cook” is the carbon tax, there should not also be green finance. But, if the carbon tax is too low, can green finance function as the “cook” instead?

Proposition 2 (Simple Green Finance) *If firms face a carbon emission tax lower than the social cost, then simple green finance may raise welfare, but cannot implement the socially optimal outcome except in the special cases in which there are no “stranded assets” and either (i) all emissions come from brown energy, $f_i^1 = 0$, (ii) all goods producers have the same*

carbon tax and scope-1 energy intensity, or (iii) all goods producers use only capital in their production, $s^i = \beta^i = 0$.

Simple green finance can achieve the socially optimal outcome in some special cases, but not in general. One reason that green finance may not work is that brown energy companies can have “stranded assets,” meaning that their negative externality is greater than their production value, such that these assets should be scrapped. To understand why green finance does not work in this case, suppose for example that electricity production by coal power plants pollutes so much that it is socially optimal to immediately close all coal plants and instead build more wind farms and other sources of energy. Naturally, a high enough carbon tax levied on such a coal plant makes burning coal uneconomic, leading to a shutdown of the coal plant as the market response. In contrast, while raising the cost of capital for the coal company can stop further investment, raising the cost of capital cannot make the company scrap existing assets.

Another reason why green finance may not work is that it only works through the investment channel. Even if such a regulation manages to incentivize firms to invest such that more capital is allocated to more sustainable technologies (those with low s_i), firms still do not have an incentive to use their capital in the most environmental way, for example in their choice of carbon intensity.

This problem with simple green finance can be overcome in special cases, however. For example, if all emissions come from brown energy—i.e., none from goods producers—then the social outcome can be achieved simply by raising the cost of capital for brown energy firms. To make green finance work more generally, we next consider whether green finance with commitment can incentivize firms to take socially optimal actions.

Proposition 3 (Green Finance with Commitment) *If firms can commit to their future actions, the social optimum can be implemented with green finance, except in the case of “stranded assets” in which brown energy should not be used at the social optimum.*

This result shows that, if someone has the power to fully control each firm’s cost of capital in a way that depends on all the firm’s actions, then the social optimum can in principle be achieved. This may be a surprising result as the lack of a Pigouvian tax is typically associated with a suboptimal outcome, but here the green finance can mimic the same effect, at least in principle. The important exception is the case of stranded assets.

In summary, green finance is not a useful supplement to an efficient carbon pricing scheme (Proposition 1) and simple green finance may not be an equally powerful alternative

to carbon pricing (Proposition 2). In the absence of stranded assets, green finance can in principle be effective with commitment (Proposition 3), but how should it be implemented? Does it require a firm-specific scheme? Is the magnitude realistic in practice? And should the cost of capital depend only on direct emissions or also on indirect ones? These are the questions we turn to next.

4.2 How Should Green Finance Be Implemented? What Scope?

Regulators, investors, firms, and other interest groups debate whether green finance should be based on carbon emissions measured as scope-1, scope-2, or scope-3 emissions, that is, only direct emissions or also indirect emissions. For example, a new industry is emerging of companies measuring other firms' emissions and certifying "carbon neutrality" if the firm offsets all emissions, often defined as scope-2 or scope-3 emissions.¹⁰ Many authors implicitly assume that scope 2 is better than scope 1, and scope 3 is better yet (if it can be measured accurately) because it is more comprehensive, but which scope actually leads to the social optimum?

In contrast, the economics literature rarely discusses the issue of scope, as the standard Pigouvian tax is levied on direct emissions, i.e., scope 1. In fact, carbon pricing can implement the social optimum in several ways in which all emissions are taxed with no double counting, including (i) all firms face a scope-1 carbon tax of T ; (ii) goods-producers face a scope-2 carbon tax of T and no carbon tax on energy companies; (iii) energy companies face scope-3 carbon tax of T and no carbon tax on goods producers.

Part (i) says that (as in Proposition 1) taxing scope 1 emissions is efficient, but why should a firm that buys a lot of electricity not be "punished"? In fact, it is punished, because taxing the electricity producer for its emissions raises electricity prices, thus incentivizing firms to reduce electricity usage. In other words, a scope 1 carbon tax affects the price of electricity and other high-emission products, thus feeding through the supply chain without a need to tax indirect emissions.

There are naturally other ways to implement the social optimum as seen from parts (ii) and (iii). If the carbon tax is only levied on goods-producing firms and these firms pay both their direct and indirect emissions (scope 2), then the social optimum is also reached — since all emissions are covered with no double counting.¹¹

¹⁰See, e.g., ["How CarbonNeutral products help companies build for the future"](#).

¹¹Such an implementation with a tax on downstream firms is especially relevant in a global context where a country can only tax domestic firms. Indeed, the country must be able to handle "leakage" due to imports

What should be the scope of green finance? Is a broader scope always better as some ESG investors and regulators appear to assume? Or, is green finance similar to carbon pricing in the sense that several schemes can achieve the social optimum?

Proposition 4 (Scope of Green Finance) *When there are no stranded assets, the social optimum can be implemented with green finance with commitment in several ways, even when carbon taxes are too low: (I) the cost capital of each firm is adjusted based on scope-1 emissions; (II) the cost of capital of goods-producing firms is raised based on scope-2 and the cost of capital of green energy is subsidized; (III) and, if $\tau_i = \tau$ and $f_i^1 = f^1$ for all i , the cost of capital for brown and green energy are increased based on scope-3 emissions.*

The proposition shows that, like carbon pricing, green finance can be implemented based on a focus on scope 1, 2, or 3. However, each method should be “tuned” correctly so that the emission externality is internalized, but not double counted, taking into account how product prices feed through the supply chain.

To show how green finance can be implemented, the next results provide explicit green finance schemes based on I, II, and III from Proposition 4. In the following, ϵ_i^* indicates the socially optimal energy intensity, and similarly for other variables with a superscript “*”.

Proposition 5 (Green Finance Implementation I) *If firms can commit to their future actions and there are no stranded assets, the social optimum can be implemented using the following green finance scheme. The cost of capital for green energy firms is $r_g = r$, for brown energy firms is $r_b = r + (\tilde{T} - \tilde{\tau}_b)F^1 a_b$, and for goods-producing firm i is*

$$r_i = \begin{cases} \bar{r}_i & \text{if } \epsilon_i = \epsilon_i^* \text{ and } L_i = L_i^* \\ \infty & \text{otherwise} \end{cases} \quad (25)$$

where $\bar{r}_i = r + \frac{s_i(r+\delta_b)(\tilde{T}-\tilde{\tau}_i)f_i^1}{p_b+\tilde{T}f_i^1}$ is increasing in the firm’s sustainability problems, s_i , the wedge between social and private emission costs, $T - \tilde{\tau}_i$, and the fossil intensity, f_i^1 . Further, when $I_b^* > 0$, it holds that $\bar{r}_i = r + \frac{s_i(r+\delta_b)(\tilde{T}-\tilde{\tau}_i)f_i^1}{\frac{r+\delta_b}{a_b}+\pi+\tilde{T}(f_i^1+F^1)}$.

This proposition shows how green finance can work with a focus on scope 1 emissions. To achieve the social optimum, brown energy firms must face a high cost of capital, that depends

from countries without carbon taxes — in the model, one can interpret the energy as imports. In that case, the country (or even better a collection of countries forming a “climate club”) must institute a form of cross-border carbon pricing, for example an import tariff that reflects all of the “embodied emissions” in the goods (Nordhaus, 2015).

on the product of their emissions intensity, F^1 , and the shortfall in the carbon tax relative to the externality, $\tilde{T} - \tilde{\tau}_b$.

Second, since green energy companies have no scope 1 emissions, their cost of capital equals the competitive rate, r .

Third, goods producing firms face a cost of capital based on (25), which means that firms only get capital if they commit to the socially optimal energy intensity and labor (and that green investors know what these socially optimal levels are). Interestingly, even though firms only get capital when committing to the optimal energy intensity and labor, firms still face different costs of capital as seen from the expression for $\bar{r}_i$ in Proposition 5. Indeed, a less sustainable firm faces a higher cost of capital. To understand why, note that while the price of energy is elevated due to the high cost of capital for the brown energy company, pollution remains “too cheap” relative to the social cost when the firm also has its own scope 1 emission, f_i^1 . Therefore, firms that pollute more are more profitable than they “should be,” so they will be tempted to invest too much at time 0, relative to the social optimum. To prevent such over-investment in unsustainable sectors, these firms must have a higher cost of capital.

Clearly, the green finance scheme of Proposition 5 is rather extreme in that the cost of capital is infinite if the firm does not commit to the right actions. More broadly, one can interpret this scheme as having a high cost of capital when the firm “misbehaves.” Alternatively, one can construct a green finance scheme such that the cost of capital is a continuous function, as considered next.

Proposition 6 (Green Finance Implementation I: Continuous) *If $\beta_i = 0$ then (25) can be replaced by a cost of capital that is firm-specific continuous function of ϵ_i :*

$$r_i(\epsilon_i) = \bar{r}_i + (\epsilon_i - \epsilon_i^*)f_i^1(1 + \bar{r}_i) \frac{(r + \delta)(1 + s_i)^2(\tilde{T} - \tilde{\tau}_i)}{\bar{r}_i + \delta + \alpha_i(1 - \delta)} \quad (26)$$

which increases in the scope-1 carbon intensity, $\epsilon_i f_i^1$.

This proposition shows that green finance can in principle be effective if a firm’s cost of capital depends on its carbon intensity, that is, its pollution. The cost of capital (26) works via two simultaneous mechanisms: First, firms with brown technologies (high s_i) face a higher baseline cost of capital (high $\bar{r}_i$ from Proposition 5) to reduce their investment. Second, firms know that their cost of capital increases in their pollution via the last term (26), especially for brown firms, incentivizing the firm to behave as if it faces a carbon tax.

Interestingly, the green finance scheme (26) depends on the firm's sustainability issues, s_i . One interpretation of this finding is that green finance should be evaluated within each industry, consistent with the real-world practice by some ESG investors who look for firms that are considered "best in class" within their industry.

Note that Proposition 6 assumes away labor choice ($\beta = 0$), because the green finance scheme (26) does not give brown firms the right incentive in their hiring decision, as browner firms are more profitable than in a world with a carbon tax. Hence, to make green finance work more generally, the cost of capital should also depend on the labor choice (but stating the precise result becomes a notational burden). The expressions also simplify when $I_b^* > 0$, and, therefore, this assumption is used in the next result on green finance focused on scope 2 emissions (the proof in the appendix contains more general results).

Proposition 7 (Green Finance Implementation II) *If firms can commit to their future actions, there are no stranded assets, and $I_b^* > 0$, then the social optimum can be implemented as follows: The cost of capital for green energy firms is $r_g = r - (\tilde{T} - \tilde{\tau}_b)F^1 a_g$, for brown energy firms is $r_b = r$, and for goods-producing firm i is given by (25) with $\bar{r}_i = r + (r + \delta_b)s_i \frac{(\tilde{T} - \tilde{\tau}_i)f_i^1 + (\tilde{T} - \tilde{\tau}_b)F^1}{\frac{\tau + \delta_b}{a_b} + \pi + \tilde{T}(f_i^1 + F^1)}$.*

In this implementation, the cost of capital for brown energy is not raised. Therefore, energy prices are too low, making green energy less profitable than it should be when externalities are priced. Therefore, the cost of capital for green energy is subsidized.

Further, the cost of capital of goods-producing firms who buy the energy must be raised substantially, for two reasons. First, to account for their own emissions (as in Proposition 6), and, second, to account for the low energy prices that fail to account for brown energy emissions. The first effect is captured via the term $f_i^1(\tilde{T} - \tilde{\tau}_i)$ in Proposition 7, and the second effect is captured via $F^1(\tilde{T} - \tilde{\tau}_b)$.

Finally, we consider the third implementation focused on energy company's scope 3 emissions. This is actually a simple green finance scheme (as discussed in Proposition 2), but it requires more restrictive assumptions.

Proposition 8 (Green Finance Implementation III) *If firms can commit to their future actions, there are no stranded assets, and all goods producers have the same carbon tax and scope-1 energy intensity, $\tau_i f_i^1 = \tau f^1$, then the social optimum can be implemented as follows: The cost of capital for green energy firms is $r_g = r + (\tilde{T} - \tilde{\tau})f^1 a_g$, for brown energy firms is $r_b = r_b = r + (\tilde{T} - \tilde{\tau}_b)F^1 a_b + (\tilde{T} - \tilde{\tau})f^1 a_b$, and for goods-producing firm i is $r_i = r$.*

In this implementation, good producers face a competitive cost of capital. The way incentives are aligned is that the high cost of capital for brown energy leads to an energy price that is increased so much that it reflects both the emissions arising from brown energy and the emissions arising from goods producers.

Given that electricity prices are raised via the brown energy firm's cost of capital, it will be raised the same for all goods producers. Therefore, this scheme only works when goods producers have the same propensity to pollute, $f_i^1 = f^1$ and when they face the same carbon tax τ_i . In contrast, a scope-3 carbon tax can in principle work more generally if the energy company is taxed on downstream emissions and can charge higher electricity prices to more polluting good producers.

In Proposition 8 even green energy firms face an elevated cost of capital. This counter-intuitive result arises because energy prices are higher than the social benefit of energy, so green energy is too profitable here. Or, as another way to think about it, green energy is used by polluting goods-producing firms, and the green energy firm is punished for this downstream pollution even though the green energy is clean itself.

In sum, green finance can be implemented in different ways, focused on different economic agents and different scopes of emissions, as long as the scheme is designed consistently and the cost of capital can be controlled. But are these schemes realistic? To evaluate this issue, we consider a calibration of the magnitude of the required changes in cost of capital.

4.3 Calibration of Green Finance

Consider first the simple calibration discussed in the introduction. In this example, the all pollution comes from the brown energy sector, i.e., $f_i^1 = 0$, and $I_b^* > 0$, which implies that the efficient outcome can be achieved by raising the cost of capital for brown energy using Proposition 5 (or Proposition 8, which is the same in this case). This proposition is applied with the following parameters: The baseline cost of capital is $r = 5\%$; the brown depreciation rate is $\delta_b = 5\%$; the fossil intensity of brown energy is $F^1 = 820 \times 10^{-6} \text{tCO}_2/\text{kWh}$ based on the median estimate of coal's lifecycle emission from Schlömer et al. (2014); the social cost of carbon emissions is $T = 43\$/\text{tCO}_2$ based on the low estimate from Nordhaus (2019); the carbon tax is $\tilde{\tau}_i = \tilde{\tau}_b = 0\$/\text{tCO}_2$; and the productivity parameters $a_b = a_g$ are chosen such that the competitive energy cost (22) is $(r + \delta_b)/a_b + \pi = 0.17\$/\text{kWh}$ based on the average cost in the US, 8/2023; and half the revenue is lost to fuel and other costs of good sold,

$(r + \delta_b)/a_b = \pi$ (i.e., a gross profit margin of 50%).¹² Based on these assumptions, the cost of capital for brown energy is given by Proposition 5 as

$$\begin{aligned}
 r_b &= r + (\tilde{T} - \tilde{\tau}_b)F^1 a_b = r + \frac{(\tilde{T} - \tilde{\tau}_b)F^1}{(r + \delta_b)/a_b}(r + \delta_b) \\
 &= 5\% + \frac{43\$/\text{tCO}_2 \times 820 \times 10^{-6}\text{tCO}_2/\text{kWh}}{0.085\$/\text{kWh}}(5\% + 5\%) \\
 &= 5\% + \frac{0.035}{0.085} \times 10\% = 5\% + 0.41 \times 10\% = 9.1\%
 \end{aligned} \tag{27}$$

In other words, a carbon tax would raise the cost of electricity by 0.035\$/kWh, which is a 41% increase relative to the contribution from the “user cost of capital,” $(r + \delta_b)/a_b = 0.085\$/\text{kWh}$. To achieve the same effect via green finance, the user cost of capital must increase by 41%, that is, by 4.1 percentage points. Since the depreciation is what it is, the cost of capital must increase by 4.1 percentage points to 9.1%.

More broadly, Table 2 shows a calibration of each of the green finance implementations I, II, and III from Propositions 5, 7, 8. For each implementation method, the table shows the cost of capital of green energy companies, brown energy companies, and three types of goods producers: green ones ($s_{i_1} = 0$, $f_{i_1}^1 = 0$), high-electricity users with no direct emissions ($s_{i_2} = 0.3$, $f_{i_2}^1 = 0$), and high-electricity users with direct emissions ($s_{i_3} = 0.3$, $f_{i_3}^1 = F^1/3$). These costs of capital are computed based on the low estimate of the social cost of carbon emissions, $T = 43\$/\text{tCO}_2$, in Panel A and a high estimate, $T = 279\$/\text{tCO}_2$, in Panel B, both from Nordhaus (2019). The other model parameters are set as before, except that the carbon emission price is $\tilde{\tau}_i = \tilde{\tau}_b = 6\$/\text{tCO}_2$ based on the empirical analysis in Section 5.3.

The first column in Table 2 shows implementation I, which is based on firms’ direct emissions. In this version of green finance, brown energy must have a large increase in cost of capital due to its significant direct emissions. The brown goods producer has a smaller increase in cost of capital since goods producers typically have much smaller direct emissions.

The second column in Table 2 shows implementation II, where the cost of capital for brown energy firms is not affected. Instead, goods producers who consume the electricity have a modestly elevated cost of capital to incentivize energy conservation. Further, green energy faces a very low cost of capital to strongly encourage green investment despite the low energy prices.

The last column in Table 2 shows implementation III, directed only at the brown and

¹²The electricity price per kWh in U.S., city average, not seasonally adjusted, is from the [Bureau of Labor Statistics](#).

Panel A. Social cost of carbon 43\$/CO2				
		I	II	III
Green energy company	r_g	5%	1.1%	6.3%
Brown energy company	r_b	8.9%	5%	10.2%
Goods producers:				
Green	$\bar{r}_{i_1}$	5%	5%	5%
High electricity, no emission	$\bar{r}_{i_2}$	5%	5.5%	5%
High electricity, high emission	$\bar{r}_{i_3}$	5.2%	5.6%	5%

Panel B. Social cost of carbon 279\$/CO2				
		I	II	III
Green energy company	r_g	5%	-23.5%	14.5%
Brown energy company	r_b	33.5%	5%	43.0%
Goods producers:				
Green	$\bar{r}_{i_1}$	5%	5%	5%
High electricity, no emission	$\bar{r}_{i_2}$	5%	6.7%	5%
High electricity, high emission	$\bar{r}_{i_3}$	5.5%	6.9%	5%

Table 2: **Green Finance Calibration: Cost of Capital.** This table shows a calibration of the green finance schemes I, II, and III from Propositions 5, 7, 8. The social cost of carbon emissions, T , is 43\$/tCO2 in Panel A and 279\$/tCO2 in Panel B based on, respectively, the conservative and high estimates of Nordhaus (2019). The table shows the cost of capital of green energy companies, brown energy companies, and three types of goods producers: green ones ($s_{i_1} = 0$, $f_{i_1}^1 = 0$), high electricity users with no direct emissions ($s_{i_2} = 0.3$, $f_{i_2}^1 = 0$), and high electricity users with direct emissions ($s_{i_3} = 0.3$, $f_{i_3}^1 = F^1/3$). The other parameters are the fossil intensity of brown energy of $F^1 = 820 \times 10^{-6}$ tCO2/kWh, the carbon emission price of $\tilde{\tau}_i = \tilde{\tau}_b = 6$ \$/tCO2, the baseline cost of capital of $r = r_i = 5\%$, all depreciation rates of 5%, and $a_b = a_g$ are chosen such that the competitive energy cost is $(r + \delta_b)/a_b + \pi = 0.17$ \$/kWh and the fuel cost, π , is half the revenue, $\pi = 0.5[(r + \delta_b)/a_b + \pi]$.

green energy companies. Here, the magnitude of the effect is large for brown energy and also non-trivial for green energy. As shown in Proposition 8, this implementation only works when all goods producing firms have the same propensity to pollute.

Looking collectively at Table 2, many of the calibrated magnitudes require changes in cost of capital that appear difficult to achieve. Indeed, green investors cannot raise the cost of capital for brown firms much if other investors step in with financing (Berk and van Binsbergen, 2023).

The most realistic scheme appears to be II, due to its focus on two things. First, the focus on buyers of brown energy requires a smaller increase in the cost of capital. Second, the focus on cheap financing for green energy can be achieved by deep-pocketed green investors. This is the approach taken by President Biden's green funding in the Inflation Reduction Act in the US, 2022. Ensuring a low cost of capital for green energy is helpful, but, in itself, it can actually lower energy prices because the green energy adds to the brown energy, so goods producers must be incentivized to use less energy via their own cost of capital.

Believers in green finance often try to turn all levers at the same time, seeking to raise the cost of capital for brown energy (as in schemes I and III), subsidize the cost of capital for green energy (as in scheme II), and raise the cost of capital for brown good producers based on their scope I and II emissions (as in scheme II).

4.4 Other Differences between Carbon Pricing and Green Finance

An advantage of carbon pricing is that it consists of a single tool, which can be applied consistently across firms. Every firm simply pays for their externality. In contrast, green finance seeks to control the cost of capital for each firm in order to reverse engineer the same effect as carbon pricing, but this requires different adjustments for different firms.

In fact, green finance is more complex to implement for a variety of reasons. To implement an optimal carbon tax, the government must measure each firm's emissions and estimate the social cost of carbon (or simply gradually increase the carbon tax), but implementing green finance requires much more. In addition to knowing emissions and the social cost of carbon, green finance also requires knowledge of the firms' production functions. Further, it requires that the regulator, investors, and financial intermediaries can jointly affect the cost of capital in the intended way.

Moreover, green finance is more susceptible to various avoidance methods by brown firms, often termed greenwashing. For example, firms may try to appear greener than they really

are in order to lower their cost of capital. Also, firms can use various corporate structures to lower their cost of capital, for instance a non-polluting firm can provide financing to a polluting firm. In this case, investors provide a low cost of capital to the parent firm, which in turn provides a low cost of capital to the subsidiary, and the pollution of the subsidiary might not be captured by the parent—in fact, even scope-2 or scope-3 emissions only capture pollution of the firm’s suppliers and buyers, not its securities.

As another example, suppose that a firm has a stranded asset. Then, as discussed in Proposition 3, a carbon tax can incentivize the firm to discontinue its use of the stranded assets, but green finance cannot. But, what if the stranded asset is bundled with a useful green asset? Said differently, what if the firm owns two assets? Clearly, carbon pricing still works and now green finance may also work if it incentivizes the firm to dispose the stranded asset by otherwise lowering the present value of joint firm via a high cost of capital. The problem with this approach is that the firm can sell off the stranded asset for a positive price, as happens in the real world, and then be left with a green asset, which typically ends up having a low cost of capital.

Another potential advantage of carbon pricing is that the government can raise a revenue from carbon taxes (or from selling carbon allowances) that can be used to reduce income taxes or other distortionary taxes. So carbon pricing can potentially lead to a so-called “double dividend,” meaning that they both reduce pollution and lead to potential economic benefits associated with a lower income tax. In contrast, green finance does not raise any revenue so it cannot be used to lower income taxes.

On the other hand, green finance has the advantage that investments can cut across borders. In other words, even if investors cannot affect the carbon tax, they can seek to instead affect the cost of capital via their investments.

5 Empirical Results

5.1 Data

The data comes from multiple sources. Quantities of carbon offsets come from the Voluntary Registry Offsets Database, developed by the Berkeley Carbon Trading Project. Similar data along with estimates of carbon offset prices are acquired from AlliedOffsets, a data vendor specialized in voluntary offsets.

Data on carbon allowances and carbon taxes come from the World Bank. Specifically,

the World Bank has data on, respectively, carbon taxes and ETS, for each region and each year, along with the percentage of global carbon emission covered by each mechanism.¹³

Futures data on European carbon allowances comes from the Intercontinental Exchange Inc (ICE). Specifically, futures prices are based on the EUA futures, using the December contract, rolled annually at the start of November. In addition to futures price levels, excess returns are computed as the ratio of prices of the same contract. As benchmarks, I also consider equity futures excess returns, using the EURO STOXX 50 from Eurex and S&P500 EMINI futures from Chicago Mercantile Exchange (CME). I also consider bond futures, using the Euro-Bund futures from Eurex, and oil futures, using the Brent Crude futures from ICE Futures Europe.

The assets under management (AUM) represented by all signatories of the Principles of Responsible Investment is reported in the 2022 PRI Annual Report. Country-level AUMs are from the PRI Historic AUM database, where each country's AUM is proxied by the sum of its asset owners' "AUM band" midpoint.¹⁴ The market values of global equity markets and global fixed income markets 2007–2021 are from the SIFMA 2022 Capital Markets Fact Book and the corresponding number from the year 2006 is from the SIFMA 2020 Capital Markets Fact Book. The members of the Network of Central Banks and Supervisors for Greening the Financial System by year is determined by accessing old versions of the website using an internet archive supplemented with annual reports.¹⁵

Global measures of gross domestic product per capita, emission per capita, and income inequality are from the World Bank,¹⁶ democracy scores are from [Economist Intelligence \(2022\)](#), and knowledge of global warming across countries is measured using a 2007 Gallup poll of "percentage reporting knowledge of global warming" (missing values are set at the median),¹⁷ and legal origins from [La Porta et al. \(2008\)](#).

5.2 Which Mechanisms Dominate?

Consider first which mechanism for emission reduction is most prevalent in the real world. To address this question, Figure 2.A plots the fraction of global emissions covered by carbon

¹³See https://carbonpricingdashboard.worldbank.org/map_data.

¹⁴The individual entity AUMs in the [PRI Historic AUM database](#) are only reported in terms of a band, where I use the midpoint and the highest level, 250+, is interpreted as [250, 500]. For the aggregate numbers, see <https://www.unpri.org/about-us/about-the-pri> and this [Excel file](#).

¹⁵The membership website <https://www.ngfs.net/en/about-us/membership> is accessed via <https://archive.org/web/>.

¹⁶The data items (indicators) are NY.GDP.PCAP.CD, EN.ATM.CO2E.PC, and SI.POV.GINI.

¹⁷<https://news.gallup.com/poll/117772/awareness-opinions-global-warming-vary-worldwide.aspx>.

taxes, carbon allowance markets (ETS), and voluntary carbon offsets, respectively, in each year of the sample from 1990 to 2022.¹⁸ The figure shows that carbon allowance markets have become the largest carbon pricing mechanism among these, followed by carbon taxes, while voluntary offsets constitute a small, but growing, market.

Notably, less than a quarter of all global emissions are subject to any of these pricing mechanisms at the end of the sample. In other words, more than three quarters of all emissions are facing a price of zero (or, in some cases, even a negative price if energy is subsidized).

The lack of carbon pricing may have led investors and regulators to consider ESG investing and sustainable finance regulation. These mechanisms are difficult to compare to the other ones since carbon taxes, allowances, and offsets are measured in terms of tCO₂e while ESG investing is measured in dollars. We can nevertheless get a sense of the prevalence of ESG investing over time as seen in Figure 2.B. This figure shows the collective assets under management (AUM) represented by all signatories of the Principles of Responsible Investment (PRI) as a fraction of the combined market value of global equity markets and global fixed income markets.¹⁹ Remarkably, signatories of the PRI manage assets worth about half of the market value of global equity and fixed income markets by the end of the sample. This number may be too high or too low: on the one hand, perhaps not all signatories act on their ESG intentions or only act with part of their assets; on the other hand, these signatories only include institutional investors, so the total size of the group of ESG investors may be even higher as it also includes many individual investors.

Further, as a measure of the coverage of sustainable finance regulation, Figure 2.B. also shows the fraction of countries with a financial regulator that is a member of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), weighted by the countries' gross domestic product (GDP). For example, 121 global financial regulators are members of NGFS as of 2023. These regulators come from 90 countries, which cover 91% of global GDP as seen in Figure 2.B. These members include, for example, Bank of Canada, Bank of England, Bank of Japan, The Central Bank of the United Arab Emirates, European Banking Authority (EBA), European Central Bank (ECB), Peoples Bank of China, Reserve

¹⁸The former two data series are from the World Bank, adding all regions, each of which is already reported in terms of fraction of global emissions covered. The later data series is attained by summing all offsets issued in each year as reported by Berkeley Carbon Trading Project, divided by the total world emissions that year as reported by <https://ourworldindata.org/co2-emissions>.

¹⁹E.g., principle 1 in PRI "signatories commitment" is: "We will incorporate ESG issues into investment analysis and decision-making processes."

Bank of Australia Reserve, Bank of India, Saudi Central Bank, and the US Federal Reserve.

While the numbers in Figures 2.A and 2.B are not directly comparable, and the numbers in 2.B might be more about intentions than actions in many cases, the implications are nevertheless striking: While economic theory suggests that carbon pricing is the optimal instrument, pledges of ESG investing and sustainable finance regulation are becoming more prevalent, although it is questionable how much action comes with such pledges.

5.3 Price Variation over Time and across Pricing Mechanisms

To study the evolution of carbon prices over time, Figures 3.A and 3.B show, for each year from 1990 to 2022, the average carbon tax across global regions, the average global carbon allowance price, and the average voluntary carbon offset price. Note that the composition of markets with such carbon pricing mechanisms varies over time, so the time series variation of carbon prices is driven both by price changes in each market and by composition changes.

We see that the prices of voluntary carbon offsets are consistently the lowest of the three categories, with a value-weighted average price just over \$5 per metric ton of carbon dioxide-equivalent emission (tCO₂e), as seen in Figure 3.B. In contrast, by the end of the sample, the value-weighted average carbon tax is 15\$/tCO₂e and the average allowance price is 27\$/tCO₂e.

Figure 3.C considers the overall global carbon emission price. This overall price is computed as the carbon-weighted average of carbon taxes, allowance prices, offset prices, and zero carbon prices for all the world's emissions that are not subject to any carbon pricing mechanism. The global carbon emission price has been growing, mostly due to the increased coverage seen in Figure 2.A, but remains way below any estimates of the social cost of carbon.

To consider the higher-frequency variation in prices, Figure 3.D shows the daily futures price for European carbon allowances. We see that prices fluctuate a lot over time, occasionally collapsing early in the sample, but trading at prices north of 75Euro/tCO₂e during the final year of the sample, a time period in which 1 Euro was approximately equal to 1 US\$. These carbon price fluctuations correlate with economic conditions as shown in Table 3. This table regresses the daily carbon futures returns on daily returns of other futures. Carbon futures returns co-vary significantly with all the other futures in univariate regressions. In the multivariate regression (8), the European carbon allowance returns only co-vary significantly with European equities (EuroStoxx is European while S&P500 is American) and European oil contracts. So, while the same outcome can in theory be achieved by a carbon tax and an

ETS if the number of allowances can adjust at each time, in practice the ETS is procyclical while a carbon tax is acyclical, like the social cost of carbon.

It is interesting to go beyond these average prices and consider the distribution of prices across markets within each type of pricing mechanism. Figure 4 reports the distribution of carbon taxes, the distribution of carbon allowance prices, and the distribution of carbon offset prices for the most recent year, 2022. Clearly these markets exhibit a wide distribution of prices, ranging up to 137\$/tCO₂e for carbon taxes, below 100\$/tCO₂e for allowances, and mostly below 20\$/tCO₂e for offsets.

To compare these price levels with their socially optimal level, consider the estimates of the social cost of carbon (SCC) reported in Nordhaus (2019): “the SCC varies greatly depending upon the policy target. For both damage functions and less ambitious temperature targets, the SCC is in the \$43–\$108 per ton range for 2020,” and, for more ambitious targets, “the SCC is in the \$158–\$279 per ton range for 2020.”

As seen from Figures 3–4, the average carbon prices are well below the range of estimates of the SCC. That said, the observed carbon prices are not orders of magnitude too low. Indeed, the distribution of observed prices has significant overlap with the range of estimates for the SCC. In other words, some regions have carbon taxes or allowance prices well above Nordhaus’s low estimate of \$43 (a number that increases over time, but is not that different for 2022 relative to 2020).

5.4 Carbon Prices in the Global Market for Offsets

It is interesting to dig deeper into the economics of the global market prices of carbon offsets. Note first that the wide distribution of offset prices observed in the right-most panels of Figure 4 is itself an interesting finding. If each offset provided a guaranteed reduction of one tCO₂e emission, then all offsets should be equivalent, so all prices should be the same. In this case, the evidence in Figure 4 presents a gross rejection of the law of one price.

These large price discrepancies are also clearly visible in Table 4. This table regresses offset prices on a constant, the registry, and the sector, leaving out one registry (Gold Standard) and one sector (Agriculture) captured in the intercept. Hence, the significant registry and sector coefficients show that there are significant price differences across registries and sectors — evidence against the law of one price for carbon offsets.

Interestingly, the price is higher for offsets in the Gold Standard registry than most of the other registries (i.e., the estimated dummy is negative for all the other registries except ACR),

consistent with the view that Gold Standard is more credible. To explore the connection between price and quality further, I construct a quality score as follows. My starting point is Table 1 in [Wissner and Schneider \(2022\)](#), which considers nine quality criteria for registries. For each registry, one is added to its quality score for each criterion that is “fulfilled,” one half is added for each “partial fulfilment”, and zero for each that is “not fulfilled,” yielding a quality score between zero and nine for the registries included.²⁰

In regression (2), offset prices are regressed on this quality score (instead of registry dummies), controlling for sectors. The quality score is seen to be positive and highly significant. This provides further evidence that the market recognizes – and puts a price on – quality differences across carbon offsets, as in my model.

5.5 Carbon Pricing and Green Finance: Neither or Both

The model suggests that green finance can be a useful alternative if direct carbon pricing is not feasible, but do countries typically have either or both tools? Table 5 reports the correlations across countries of their carbon pricing, sustainable finance regulation, and level of ESG investing.

Here, each country’s average carbon emission price is the sum of all the country’s carbon taxes multiplied their fraction of the country’s emissions covered, plus the carbon allowance price times the fraction of emissions covered by an emission trading system, plus zero times the fraction of emissions not covered by any carbon pricing mechanism. For example, if a country does not have any carbon pricing mechanisms, the average price is zero, or, if half of the country’s emissions face a tax of \$50, then the average price is \$25. This carbon price is measured at the end of the sample, in 2022.

Further, ESG investing is measured as each country’s PRI signatory AUM (computed as described in Section 5.1) as a fraction of GDP, and sustainable finance regulation is proxied by membership in the Network of Central Banks and Supervisors for Greening the Financial System, both measured at the end of the sample.

As seen in the Table 5, each pairwise correlation is positive and highly significant, suggesting that countries tend to have multiple tools, or none. The next section considers which societal conditions are linked to carbon pricing and green finance, respectively, and whether these links can help explain the positive correlation between carbon pricing and

²⁰Registries not included in Table 1 in [Wissner and Schneider \(2022\)](#) are not used in regression (2), which therefore has fewer observations than regression (1) as seen in Table 1.

green finance.

5.6 Carbon Prices and Green Finance Across Countries

The positive link between carbon pricing and green finance highlighted in Table 5 is related to the fact that both tend to be higher for wealthier countries, as seen in Figure 5. Indeed, the left panel in this figure shows the average carbon emission price across 148 countries plotted against their wealth levels (measured as GDP per capita), and the right panel shows the ESG investing plotted against wealth. The positive relations between wealth and, respectively, carbon pricing and ESG are statistically significant as seen in Table 6.

Table 6 further considers several other measures of economic and societal conditions. The table shows that carbon pricing is positively linked to wealth, democracy, knowledge of global warming, and negatively related to income inequality, and the country's emissions in the year 2000 (before most countries started implementing carbon pricing measures). Table 6 also shows that ESG investing is positively linked to wealth while sustainable finance regulation is positively related to democracy and emissions.

What explains this global variation in carbon pricing and green finance? While a truly causal analysis is beyond the scope of this paper, it is nevertheless interesting to consider what costs and benefits might drive this variation.

From the perspective of a government, carbon pricing should be viewed as an effective tool to lower emissions, but a government may only have the political will to implement carbon pricing if the citizens believe that they can afford such a policy, the population is knowledgeable of global warming, the country is not too dependent on carbon emissions, and if it has a sufficient sense of community arising from a democratic tradition and limited inequality.

If the government does not take such action, others may try to act independently. In particular, owners of capital cannot implement carbon pricing, but can pursue ESG investing. Not surprisingly, capital owners in wealthier countries more readily pursue such non-financial goals. This finding is consistent with causal evidence from micro data in Denmark ([Andersen et al., 2023](#)).

In a similar spirit, central banks and other civil servants who want to fight climate change may be able to implement sustainable finance regulation, but not carbon pricing. Based on the regressions, such civil servants appear more likely to pursue this strategy in democracies with high emissions.

Lastly, Table 6 shows that carbon pricing and green finance are linked to the country's legal origin. Consistent with the view that common law seeks to “support private market outcomes, whereas civil law seeks to replace such outcomes with state-desired allocations” (La Porta et al., 2008), Table 6 shows that carbon pricing and sustainable finance regulation are lower among common law countries (English legal origin), while ESG investing in common law countries is not significantly different from that in civil law countries based on French and German law.

6 Conclusion: Everything, Everywhere, All at Once?

The UN secretary general, António Guterres, recently stated that “our world needs climate action on all fronts — everything, everywhere, all at once”²¹ and, indeed, global climate action is proliferating in various forms of carbon pricing and green finance. This proliferation stands in contrast to the recommendation from economics that climate change should be fought using a single tool everywhere at once—a carbon tax.

However, if carbon pricing is not politically feasible, then other approaches are needed. To capture the UN's “everything” approach, this paper presents a workhorse model that unifies a range of carbon-pricing and green-finance approaches. The model is general, yet simple and tractable. The model yields several clear predictions. The model shows that green finance can in principle be effective if the cost of capital can be sufficiently controlled by the joint efforts of ESG investors and regulators, but the problems with stranded assets cannot be solved in a timely manner via green finance.

Further, the model shows how to “translate” a carbon tax rate to green finance terms. I present the functional form of optimal green finance schemes and calibrate the needed changes in the cost of capital, which appear beyond what is currently observed. So green finance is no panacea. Lastly, I examine green finance and carbon pricing empirically.

Based on my findings, UN's call for “everything, everywhere, all at once” is likely not an attempt for optimality, but a second-best attempt of taking many small steps when the optimal leap is unattainable.

²¹<https://www.un.org/sg/en/content/sg/statement/2023-03-20/secretary-generals-video-message-for-press-conference-launch-the-synthesis-report-of-the-intergovernmental-panel-climate-change>

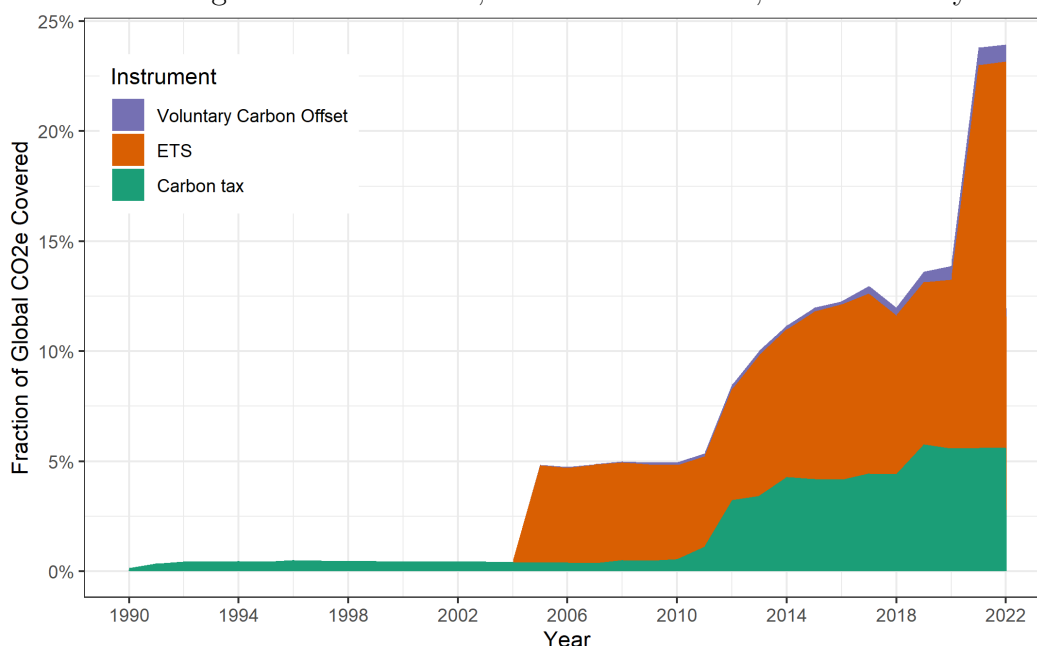
References

- Acharya, V. V., R. Berner, R. Engle, H. Jung, J. Stroebe, X. Zeng, and Y. Zhao (2023). Climate stress testing. *Annual Review of Financial Economics* 15, 291–326.
- Alankar, A. and M. Scholes (2022). Carbon emissions and asset management. *Journal of Investment Management* 20(4), 5–16.
- Andersen, S., D. Chebotarev, F. Z. F. Adib, and K. M. Nielsen (2023). Rich and responsible? the rise of responsible investors. *Working paper, Copenhagen Business School*.
- Andersson, J. J. (2019). Carbon taxes and CO2 emissions: Sweden as a case study. *American Economic Journal: Economic Policy* 11(4), 1–30.
- Arnold, L. G. (2023). On the neutrality of socially responsible investing: The general equilibrium perspective. *Theoretical Economics* 18(1), 65–95.
- Baker, M., D. Bergstresser, G. Serafeim, and J. Wurgler (2022). The pricing and ownership of us green bonds. *Annual Review of Financial Economics* 14.
- Berg, F., J. F. Koebel, and R. Rigobon (2022). Aggregate confusion: The divergence of esg ratings. *Review of Finance* 26(6), 1315–1344.
- Berk, J. and J. H. van Binsbergen (2023). The impact of impact investing.
- Bolton, P. and M. Kacperczyk (2021). Do investors care about carbon risk? *Journal of financial economics* 142(2), 517–549.
- Calel, R., J. Colmer, A. Dechezleprêtre, and M. Glachant (2021). Do carbon offsets offset carbon? *CESifo Working Paper*.
- Daniel, K. D., R. B. Litterman, and G. Wagner (2019). Declining co2 price paths. *Proceedings of the National Academy of Sciences* 116(42), 20886–20891.
- Dávila, E. and A. Walther (2022). Corrective regulation with imperfect instruments.
- Diamond, P. A. (1973). Consumption externalities and imperfect corrective pricing. *The Bell Journal of Economics and Management Science*, 526–538.
- Economist Intelligence (2022). Democracy index 2022: Frontline democracy and the battle for ukraine. *EIU*.
- Eskildsen, M., M. Ibert, T. I. Jensen, and L. H. Pedersen (2023). In search of the true greenium. *Working paper, Copenhagen Business School*.
- Feldhütter, P. and L. H. Pedersen (2022). Is capital structure irrelevant with esg investors? *Working paper, Copenhagen Business School*.

- Flammer, C. (2013). Corporate social responsibility and shareholder reaction: The environmental awareness of investors. *Academy of Management journal* 56(3), 758–781.
- Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics* 142(2), 499–516.
- Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica* 82(1), 41–88.
- Gormsen, N. J., K. Huber, and S. S. Oh (2023). Climate capitalists. *Working paper, University of Chicago*.
- Hartzmark, S. M. and K. Shue (2023). Counterproductive impact investing: The impact elasticity of brown and green firms. *Working paper, Boston College*.
- Hong, H. and M. Kacperczyk (2009). The price of sin: The effects of social norms on markets. *Journal of financial economics* 93(1), 15–36.
- Hong, H., N. Wang, and J. Yang (2021). Welfare consequences of sustainable finance.
- Känzig, D. R. (2022). The unequal economic consequences of carbon pricing. *Working paper, Northwestern University*.
- Kaplan, R. S., K. Ramanna, and M. Roston (2023). Accounting for carbon offsets—establishing the foundation for carbon-trading markets. *Working paper, Harvard Business School*.
- La Porta, R., F. Lopez-de Silanes, and A. Shleifer (2008). The economic consequences of legal origins. *Journal of economic literature* 46(2), 285–332.
- Nobel Committee (2018). Economic growth, technological change, and climate change. *Scientific Background on the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2018*.
- Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review* 105(4), 1339–1370.
- Nordhaus, W. (2019). Climate change: The ultimate challenge for economics. *American Economic Review* 109(6), 1991–2014.
- Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. *Science* 258(5086), 1315–1319.
- Nordhaus, W. D. (1994). *Managing the global commons: the economics of climate change*, Volume 31. MIT press Cambridge, MA.
- Pástor, L., R. F. Stambaugh, and L. A. Taylor (2021). Sustainable investing in equilibrium. *Journal of Financial Economics* 142(2), 550–571.

- Peck, S. C. and T. J. Teisberg (1992). Ceta: a model for carbon emissions trajectory assessment. *The Energy Journal* 13(1).
- Pedersen, L. H., S. Fitzgibbons, and L. Pomorski (2021). Responsible investing: The ESG-efficient frontier. *Journal of Financial Economics* 142(2), 572–597.
- Schlömer, S., T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, and R. Wiser (2014). Annex iii: Technology-specific cost and performance parameters. In *Climate change 2014: Mitigation of climate change: Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*, pp. 1329–1356. Cambridge, UK: Cambridge University Press.
- The World Bank (2022). State and trends of carbon pricing 2022.
- Wissner, N. and L. Schneider (2022). Ensuring safeguards and assessing sustainable development impacts in the voluntary carbon market. *White paper, Oeko-Institut e.V.*

Panel A: Coverage of Carbon Taxes, Allowance Markets, and Voluntary Offsets



Panel B: Coverage of ESG Investing and Sustainable Finance Regulation

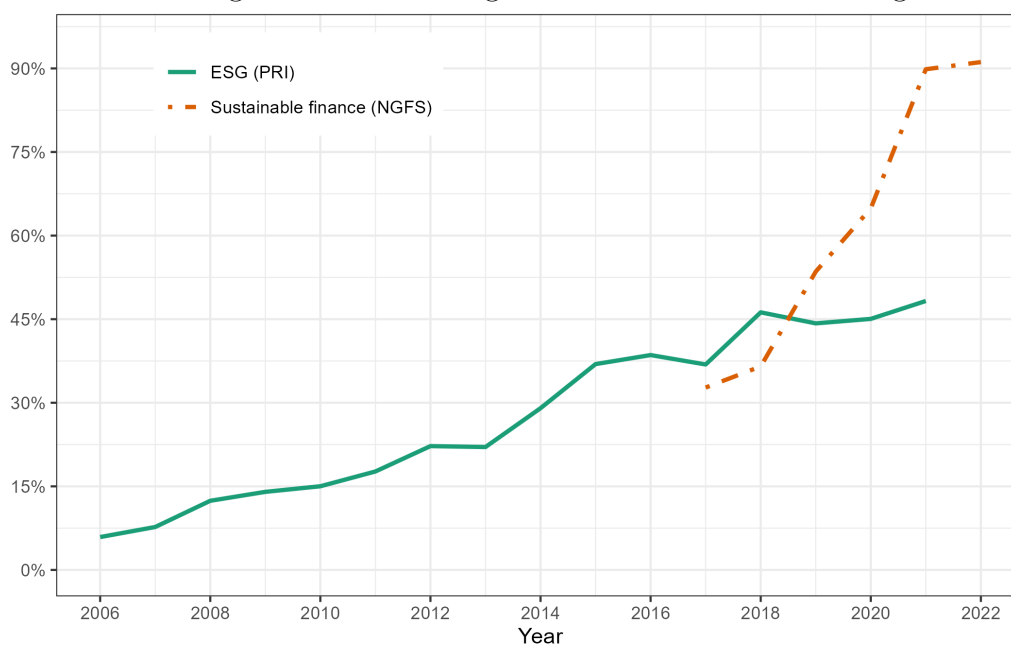


Figure 2: Global Coverage of Carbon Pricing and Green Finance

Note: Panel A of this figure shows the fraction of global emissions covered by carbon taxes, carbon allowance markets (ETS), and voluntary carbon offsets. The solid line in Panel B shows the collective assets under management (AUM) represented by all signatories of the Principles of Responsible Investment as a fraction of the combined market value of global equity markets and global fixed income markets (SIFMA 2022 Capital Markets Fact Book). The dash-dotted line in Panel B shows, for each year, the total GDP of all countries with a regulator that is a member of The Network of Central Banks and Supervisors for Greening the Financial System (NGFS), as a fraction of global GDP.

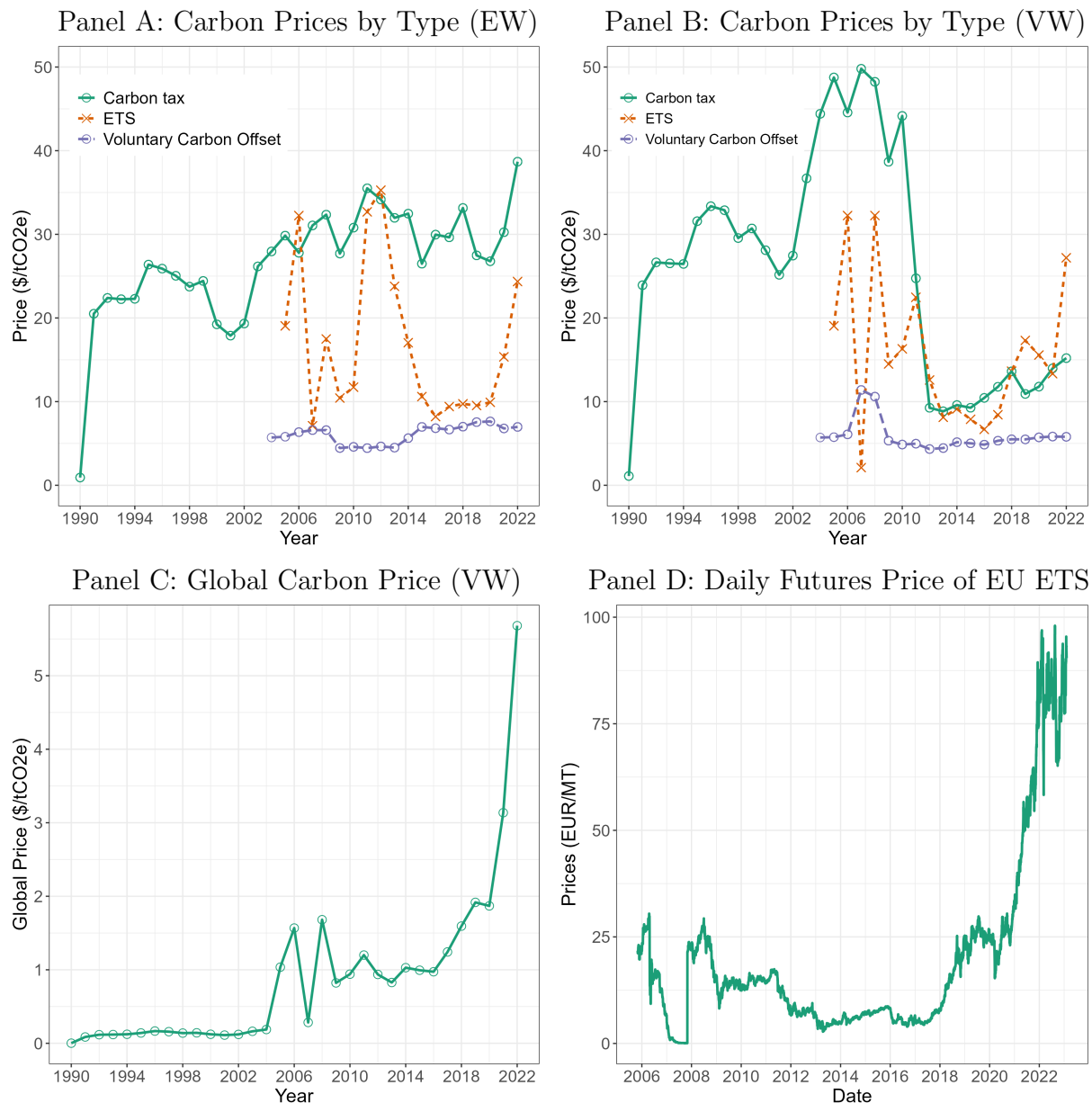


Figure 3: Carbon Prices Over Time

Note: Panel A shows three time annual series of carbon pricing, measured in US\$ per metric ton of carbon dioxide-equivalent emission (\$/tCO₂e): the average carbon taxes across global regions that have such taxes during the given year (diamond shaped markers), the average of global ETS carbon allowance prices (triangle markers), and the average of voluntary carbon offset prices across the global registries in my sample (square markers). Panel B plots the same with value-weighting, meaning that each price is weighted by the amount of carbon it covers. Panel C shows the overall “global carbon price” computed as the average of all carbon prices from Panels A and B, weighted by the amount of carbon covered, including a price of zero for carbon not covered by any pricing mechanism. Panel D shows daily futures prices for European ETS.

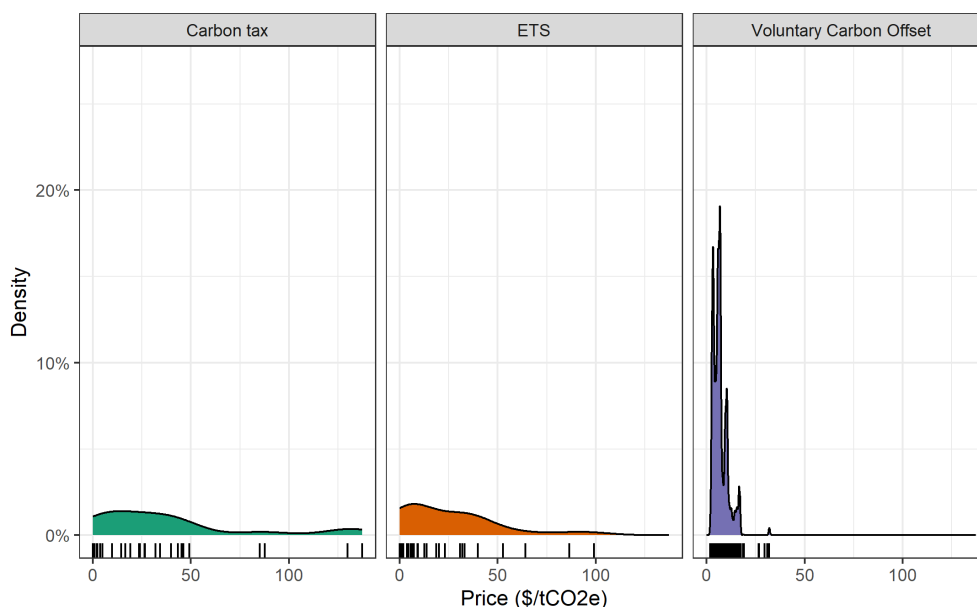


Figure 4: **Distribution of Global Carbon Prices**

Note: The figure shows the 2022 distribution of global carbon taxes across global regions (“Carbon tax”), the distribution of carbon allowances prices in global emission trading systems (“ETS”), and the distribution of voluntary carbon offset prices (“Voluntary Carbon Offset”), measured as US\$ per metric ton of carbon dioxide-equivalent emission (\$/tCO₂e). In addition to the density plots, each observation is shown as a æline below each plot.

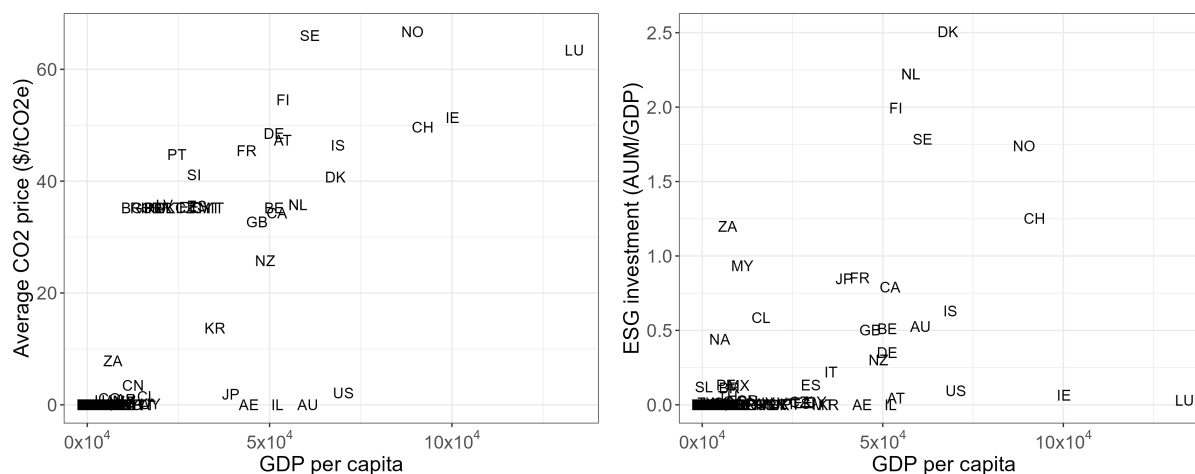


Figure 5: **Emission Price and ESG vs. Wealth across Countries**

Note: The left panel of this figure shows the average carbon emission price across countries plotted against wealth (GDP per capita). The right panel shows the ESG investing across countries plotted against wealth. Here, each country’s average carbon emission price is the sum of all the country’s carbon taxes multiplied their fraction of the country’s emissions covered, plus the carbon allowance price times the fraction of emissions coverage, plus zero times the fraction of emissions not covered by any carbon pricing mechanism. ESG investing is measured as the Principles of Responsible Investment asset under management divided by GDP, where the country-level AUM is from the PRI Historic AUM database and each country’s AUM is proxied by the sum of its asset owners’ “AUM band” midpoint.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Brentoil	0.27*** (0.02)							0.10** (0.03)
Gasoil		0.30*** (0.02)						0.15*** (0.04)
EuroStoxx			0.42*** (0.04)					0.24*** (0.05)
SP500				0.35*** (0.04)				0.06 (0.05)
EuroBund					-1.78*** (0.28)			-0.50 (0.30)
Aluminium						0.22*** (0.04)		0.01 (0.04)
Corn							0.13*** (0.03)	0.02 (0.03)
Adj. R^2	0.03	0.03	0.03	0.02	0.01	0.01	0.00	0.05
Observations	4508	4508	4508	4508	4508	4508	4508	4508

Table 3: **Time Series Regression of EU ETS on Explanatory Variables**

Note: This table shows the regression of daily excess returns of futures on European carbon allowances (EUCO2) on excess returns of futures on various economic variables, 11/1/2005–2/9/2023.

	<i>Dependent variable:</i>	
	Est. Retirement Price	
	(1)	(2)
Constant	5.97*** (0.08)	2.44*** (0.26)
Registry		
ACR	0.50*** (0.04)	
CAR	-0.42*** (0.03)	
ACORN	-0.80** (0.32)	
NOR	-1.18*** (0.08)	
VCS	-2.52*** (0.01)	
Peatland	-2.76*** (0.11)	
Woodland	-2.80*** (0.04)	
CCA	-3.66*** (0.04)	
Plan Vivo	-3.75*** (0.05)	
CDM	-3.94*** (0.03)	
Registry Quality Score		0.51*** (0.002)
Sector		
Chemical Processes/Industrial Manufacturing	0.75*** (0.08)	0.14 (0.26)
Energy Efficiency/Fuel Switching	3.83*** (0.08)	2.79*** (0.26)
Forestry and Land Use	4.10*** (0.07)	3.03*** (0.26)
Household Devices	3.78*** (0.08)	2.74*** (0.26)
Renewable Energy	-0.07 (0.07)	-1.10*** (0.26)
Transportation	-1.12*** (0.11)	-0.34 (0.32)
Waste Disposal	0.59*** (0.07)	0.29 (0.26)
Other	8.19*** (0.08)	7.14*** (0.26)
R^2	0.70	0.70
Observations	288,046	269,536

Table 4: **Carbon Offset Prices vs. Quality of Offset**

Note: The table shows the regression of voluntary carbon offset prices on several explanatory variables. In regression (1), the explanatory variables are a constant, dummies for the registry, and dummies for the sector. The constant represents the average price for the registry and sector that are left out, namely Gold Standard (the registry with the highest quality score) and Agriculture. The other coefficients represent the price difference relative to this benchmark. In regression (2), the registry dummies are replaced with a registry quality score (higher score corresponds to higher quality). Standard errors are reported in parenthesis and p -values are indicated as * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Panel A: Correlations				Panel B: <i>t</i> -statistics			
	CO2 price	NGFS	ESG		CO2 price	NGFS	ESG
CO2 price	1			CO2 price			
NGFS	0.47	1		NGFS	7.31		
ESG	0.50	0.34	1	ESG	7.99	4.93	

Table 5: **Do Countries Have Carbon Prices or Green Finance or Both?**

Note: Panel A reports correlations across countries of their average emission price (CO2-price), membership of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS, either 0 or 1), and the assets under management for asset owners who signed the Principles of Responsible Investing as a fraction of GDP (ESG). Each country's average carbon emission price is the sum of all the country's carbon taxes multiplied their fraction of the country's emissions covered, plus the carbon allowance price times the fraction of emissions coverage, plus zero times the fraction of emissions not covered by any carbon pricing mechanism.

	CO2 price		ESG		NGFS	
Constant	5.93 (5.98)	2.93 (5.65)	-0.13 (0.22)	-0.18 (0.19)	-0.01 (0.23)	0.05 (0.23)
GDP/capita	5.35*** (0.68)	4.79*** (0.68)	0.11*** (0.03)	0.05** (0.02)	-0.01 (0.03)	-0.01 (0.03)
Democracy	1.42*** (0.50)	1.49*** (0.50)	0.03* (0.02)	0.03** (0.02)	0.10*** (0.02)	0.11*** (0.02)
Knowl. of global warming	10.44* (5.80)	3.35 (5.68)	0.09 (0.22)	-0.01 (0.19)	0.21 (0.23)	0.08 (0.23)
Inequality (Gini)	-0.42*** (0.12)	-0.25** (0.11)	-0.00 (0.00)	0.00 (0.00)	-0.01 (0.00)	-0.01 (0.00)
Emission/capita in 2000	-0.89*** (0.30)	-0.59* (0.30)	-0.02* (0.01)	0.00 (0.01)	0.02** (0.01)	0.03** (0.01)
Legal origin						
English		-4.08** (1.97)		-0.03 (0.07)		-0.21** (0.08)
German		9.18*** (2.58)		-0.10 (0.09)		-0.15 (0.11)
Scandinavian		14.01*** (5.03)		1.19*** (0.17)		-0.20 (0.21)
Socialist		1.22 (9.63)		0.12 (0.33)		0.01 (0.40)
R^2	0.69	0.74	0.36	0.54	0.41	0.44
Num. obs.	148	148	148	148	148	148

Table 6: **Carbon Price and Green Finance vs. Societal Conditions**

Note: This table reports the regressions across countries with dependent variables of, respectively, their average emission price (CO2-price); assets under management of asset owners who signed the Principles of Responsible Investing in country as a fraction of GDP (ESG); and membership of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS, either 0 or 1), each measured at the end of the sample. The right-hand-side variables include the countries' GDP per capita divided by 10,000, democracy score, income inequality, emission per capita in 2000, and legal origin (where French legal origin is in the intercept). Each country's average carbon emission price is the sum of all the country's carbon taxes multiplied their fraction of the country's emissions covered, plus the carbon allowance price times the fraction of emissions coverage, plus zero times the fraction of emissions not covered by any carbon pricing mechanism. Standard errors are reported in parenthesis and *p*-values are indicated as **p* < 0.1, ***p* < 0.05, and ****p* < 0.01.

A Appendix: Equilibrium Price of Carbon Allowances

Equilibrium Price of Carbon Allowances

Until now, the model was based on an exogenous tax on carbon emissions, τ_i . Suppose instead that all firms must buy carbon allowances in order to emit carbon at an endogenous price of τ . Specifically, any firm must buy a number of carbon allowances equal to its emissions net of offsets, $\epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_{i,q}$. Hence, with a price of carbon allowances given by τ , the firm's problem becomes

$$\max_{L_i, \epsilon_i, (o_{i,q})} \Pi_i = Y_i - wL_i - \tau(\epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_{i,q})^+ - \sum_q o_{i,q} \phi_q \quad (\text{A.1})$$

This firm optimization is the same as the original one (5), except that the common price of carbon allowances, τ , is now determined in equilibrium such that the sum of all emissions net of offsets equals a fixed cap, $\bar{C}$:

$$\sum_i \left(\epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_{i,q} \right) \leq \bar{C} \quad (\text{A.2})$$

Naturally, for every tax rate, there exists an equivalent level of the carbon cap.

Proposition 9 (Cap-and-Trade) *There exists a level $\bar{C}$ of total carbon allowances such that the market equilibrium is socially optimal when all firms are required to buy carbon allowance or high-quality offsets, $\bar{q}_i = 1$, required returns are competitive, $r_i = r$, and $\tau_w = 0$.*

B Appendix: Proofs

Proof of Proposition 1. The planner faces a social cost of carbon emission of $\tilde{T}$ given by (24), and the planner's problem can be written as maximizing social utility U by choosing $(\epsilon_i, L_i, K_i), I_g, I_b, x_b$:

$$U = (1 + r)(W - \sum_i I_i - I_g - I_b) + \sum_i (Y_i - \bar{w}L_i) - \frac{\xi}{2} I_g^2 - \pi x_b + K' - \tilde{T} \times \text{CO2}^{\text{total}}$$

where $\text{CO2}^{\text{total}} = (\sum_i f_i^1 \epsilon_i Y_i + F^1 x_b)$, $K' = \sum_i (1 - \delta) K_i + (1 - \delta_b) K_b + (1 - \delta_g) K_g$, and $x_b = a_b(I_b + K_b 1_{\{\text{use}\}})$. The utility, U , can be rewritten as follows, where I leave out the

constant terms, $(1+r)W + (1-\delta_b)\bar{K}_b$:

$$\begin{aligned}
U &= -(1+r)\left(\sum_i I_i + I_b + I_g\right) - \frac{\xi}{2}I_g^2 + \sum_i (Y_i - \bar{w}L_i) - \pi x_b + K' - \tilde{T} \left(\sum_i f_i^1 \epsilon_i Y_i + F^1 x_b \right) \\
&= -(r + \delta_b)I_b - (\pi + \tilde{T}F^1)x_b - (r + \delta_g)K_g - \frac{\xi}{2}K_g^2 + \sum_i \left((1 - \epsilon_i \tilde{T}f_i^1)Y_i - \bar{w}L_i - (r + \delta)K_i \right) \\
&= -\left(\frac{r + \delta_b}{a_b} + \pi + \tilde{T}F^1\right)a_b I_b - (\pi + \tilde{T}F^1)a_b \bar{K}_b 1_{\{\text{use}\}} - (r + \delta_g)K_g - \frac{\xi}{2}K_g^2 \\
&\quad + \sum_i \left((1 - \epsilon_i \tilde{T}f_i^1)a_i \epsilon_i^{s_i} L_i^{\beta_i} K_i^{\alpha_i} - \bar{w}L_i - (r + \delta)K_i \right)
\end{aligned} \tag{B.1}$$

The planner chooses (ϵ_i, L_i, K_i) , K_g and then I_b and $1_{\{\text{use}\}}$ follow from the resource constraint (corresponding to the market-clearing condition), $a_b(I_b + \bar{K}_b 1_{\{\text{use}\}}) = \sum_i \epsilon_i Y_i - a_g K_g$.

Suppose first that the constraint $I_b \geq 0$ is not binding, which also means that $1_{\{\text{use}\}} = 1$. Then we can insert $a_b I_b = \sum_i \epsilon_i Y_i - a_g K_g - a_b \bar{K}_b$ into the planner's problem (B.1), defining p^* and p_i^* as

$$p_i^* = p^* + \tilde{T}f_i^1 \tag{B.2}$$

and

$$p^* = \frac{r + \delta_b}{a_b} + \pi + \tilde{T}F^1 \tag{B.3}$$

which yields

$$\begin{aligned}
U &= -p^* \left(\sum_i \epsilon_i Y_i - a_g K_g - a_b \bar{K}_b \right) - (\pi + \tilde{T}F^1)a_b \bar{K}_b - (r + \delta_g)K_g - \frac{\xi}{2}K_g^2 \\
&\quad + \sum_i \left((1 - \epsilon_i \tilde{T}f_i^1)a_i \epsilon_i^{s_i} L_i^{\beta_i} K_i^{\alpha_i} - \bar{w}L_i - (r + \delta)K_i \right) \\
&= [p^* a_g - (r + \delta_g)]K_g - \frac{\xi}{2}K_g^2 + \sum_i \left((1 - \epsilon_i p_i^*)a_i \epsilon_i^{s_i} L_i^{\beta_i} K_i^{\alpha_i} - \bar{w}L_i - (r + \delta)K_i \right) \\
&\quad + (p^* - \pi - \tilde{T}F^1)a_b \bar{K}_b
\end{aligned} \tag{B.4}$$

The planner's problem (B.4) has the following first order conditions.

$$\epsilon_i = \frac{s_i}{1 + s_i p_i^*} \frac{1}{p_i^*} \quad (\text{B.5})$$

$$L_i = \left(\frac{\beta_i a_i \left(\frac{s_i}{1 + s_i p_i^*} \right)^{s_i} \frac{1}{1 + s_i} K_i^{\alpha_i}}{\bar{w}} \right)^{\frac{1}{1 - \beta_i}} \quad (\text{B.6})$$

$$K_i = \left((r + \delta)^{-1} \left[a_i \left(\frac{s_i}{1 + s_i p_i^*} \right)^{s_i} \frac{1}{1 + s_i} \right]^{\frac{1}{1 - \beta_i}} \bar{w}^{-\frac{\beta_i}{1 - \beta_i}} \beta_i^{\frac{\beta_i}{1 - \beta_i}} \alpha_i \right)^{\frac{1 - \beta_i}{1 - \alpha_i - \beta_i}} \quad (\text{B.7})$$

$$K_g = \frac{1}{\xi} (p^* a_g - (r + \delta_g)) \quad (\text{B.8})$$

Finally, we can solve for I_b by inserting (B.5)–(B.8) into $a_b I_b = \sum_i \epsilon_i Y_i - a_g K_g - a_b \bar{K}_b$. If the resulting $I_b \geq 0$, then we have the solution to the planner's problem.

Further, this solution equals the market equilibrium, which is seen as follows. The market equilibrium electricity price is $p_b = p_g = p^*$ as explained in Section 3.4, under the assumptions stated in the proposition. Therefore, the effective energy cost for goods-producing any firm is $\bar{p}_i = p^* + \tilde{T} f_i^1 = p_i^*$, so (B.5) coincides with (12), (B.6) with (15), (B.7) with (17), (B.8) is the solution to (20), and the brown energy company is happy to clear the energy market.

Suppose instead that $I_b < 0$ when we solve (B.5)–(B.8). Then, we must have $I_b = 0$. In this case, the solution to the planner's problem remains (B.5)–(B.8), but now p^* is no longer given by (B.3), but instead p^* is the Lagrange multiplier corresponding to the planner's resource constraint with $I_b = 0$, that is, $0 = \sum_i \epsilon_i Y_i - a_g K_g - a_b \bar{K}_b 1_{\{p^* \geq \tilde{T} F^1\}}$. Hence, we choose the p^* that satisfies this constraint.

Again, the solution to the planner's problem equals the market equilibrium. The electricity price is $p_b = p_g = p^*$. As before, the energy cost for any goods-producing firm is $\bar{p}_i = p^* + \tilde{T} f_i^1 = p_i^*$, so (B.5) coincides with (12), (B.6) with (15), (B.7) with (17), and (B.8) is the solution to (20). Further, the brown energy company chooses $I_b = 0$ because $p^* < \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1$. To see that, recall that a price of $p^* = \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1$ from (B.3) results in $a_b I_b = \sum_i \epsilon_i Y_i - a_g K_g - a_b \bar{K}_b < 0$, so, to clear the energy market, p^* must be lower so that $\sum_i \epsilon_i Y$ is higher and $a_g K_g$ is lower. Further, the brown energy company disposes of the existing assets when $p^* < \pi + \tilde{T} F^1$.

□

Proof of Proposition 2. When some firms face an effective carbon emission cost lower than the social cost, $\min\{\tau_i, \phi_{\bar{q}_i}\} < \min\{T, \phi_1\}$, then they naturally face a lower total energy

cost than the social cost, that is, $\bar{p}_i < p_i^*$, where $\bar{p}_i = p_b + \min\{\tau_i, \phi_{\bar{q}_i}\}f_i^1$ and p_i^* is the analogous social cost defined in (B.2). Therefore, such a firm chooses a energy intensity (12), labor (15), and investment (17) that are distorted relative to the social optimum (B.5)–(B.7). The cost of capital r_i affects the investment, and, since the utility of the representative household, U , is below the social optimum, it holds for generic parameters that $\partial U / \partial r_i \neq 0$. Hence, changing r_i from r can increase utility.

However, even if r_i can be controlled such that investment reaches its socially optimal level, then the associated equilibrium is nevertheless still not socially optimal. To see this, note that firms choose a too high energy intensity (12) relative to the social optimum (B.5) whenever $\bar{p}_i < p_i^*$, with resulting knock-on effects on labor choice (B.6).

These suboptimal choices of labor and energy intensity are clearly not relevant in the special case in which all goods producers use only capital in their production, $s^i = \beta^i = 0$.

Also, in the special cases in which all emissions come from brown energy, $f_i^1 = 0$, or all goods producers have the same carbon tax and scope-1 energy intensity, then the social optimum can be implemented by the scheme in Proposition 8, which is a simple green finance scheme.

With stranded assets, green finance cannot work for the following reason. Given any price of energy net of carbon taxes, $p_b - \tilde{\tau}_b F_b > 0$, the brown energy company has an NPV of $\Pi_b = \frac{(p_b - \tilde{\tau}_b F_b)a_b(I_b + \bar{K}_b 1_{\{\text{use}\}}) + (1 - \delta_b)(I_b + \bar{K}_b)}{1 + r_b} - I_b$, so raising the cost of capital r_b can make it optimal for the company to choose $I_b = 0$, but no $r_b \in (0, \infty)$ can make it optimal to dispose of the assets, $1_{\{\text{use}\}} = 0$, since disposing implies $\Pi_b = 0$ while not disposing implies $\Pi_b > 0$. $\square$

Proof of Proposition 3. The fact that green finance with commitment can implement the social optimum is shown by construction in the proofs of Propositions 4–8 without stranded assets. With stranded assets, green finance cannot work for the reason given in the proof of Proposition 2. $\square$

Proof of Proposition 4. Indicate by “*” the socially optimal choices, as derived in the proof of Proposition 1, and assume that scope-1 carbon taxes are below their social optimum. For each case (I)–(III), we need to set the cost of capital for (a) brown energy, (b) green energy, and (b) goods-producing firms, such that the market equilibrium equals the social optimum.

Suppose first that there is brown energy investment in the social optimum, $I_b^* > 0$:

(I.a) Let $r_b = r + (\tilde{T} - \tilde{\tau}_b)a_b F^1$ be the cost of capital for brown energy. Conjecture that $p_b = \frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F^1 = \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1 = p^*$ using (B.3).

(I.b) Let $r_g = r$, which leads to $K_g = K_g^*$ given that $p_b = p^*$ as seen from (B.8).

(I.c) Choose r_i as in Proposition 5 such that goods producers behave as if their cost of energy is $\bar{p}_i = p^* + \tilde{T} f_i^1 = p_i^*$ in terms of their choice of energy intensity, labor, and investment. In this case, p_b clears the market.

(II.a) Let $r_b = r$ so $p_b = \frac{r + \delta_b}{a_b} + \pi + \tilde{\tau}_b F^1 < \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1 = p^*$.

(II.b) Choose r_g so that $K_g = K_g^*$, that is, $\frac{1}{\xi}(p_b a_g - (r_g + \delta_g)) = \frac{1}{\xi}(p^* a_g - (r + \delta_g))$. The solution is $r_g = r - a_g(p^* - p_b) = r - (\tilde{T} - \tilde{\tau}_b)a_g F^1$.

(II.c) Choose r_i as in Proposition 7 such that goods producers behave as if their cost of energy is $\bar{p}_i = p_b + (\tilde{T} - \tilde{\tau}_b)F^1 + \tilde{T} f_i^1 = p_i^*$ in terms of their choice of energy intensity, labor, and investment.

(III.a) Let $r_b = r + (\tilde{T} - \tilde{\tau}_b)a_b F^1 + (\tilde{T} - \tilde{\tau})a_b f^1$, where $\tilde{\tau}_i = \tilde{\tau}$ and $f_i^1 = f^1$ for all i by assumption. Hence, $p_b = \frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F^1 = \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1 + (\tilde{T} - \tilde{\tau})f^1$.

(III.b) Choose r_g so that $K_g = K_g^*$, that is, $\frac{1}{\xi}(p_b a_g - (r_g + \delta_g)) = \frac{1}{\xi}(p^* a_g - (r + \delta_g))$. The solution is $r_g = r - a_g(p^* - p_b) = r + (\tilde{T} - \tilde{\tau})a_g f^1$.

(III.c) Choose $r_i = r$. Goods producers face a cost of energy of $\bar{p}_i = p_b + \tilde{\tau} f_i^1 = p_i^*$, which equals the social cost.

Consider next the case in which $I_b^* = 0$. Then the cases change as follows:

(I.a) As before, let $r_b = r + (\tilde{T} - \tilde{\tau}_b)a_b F^1$ and conjecture that $p_b = p^*$, but now $p^* < \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1$ as discussed in the proof of Proposition 1. Therefore, the brown energy company optimally chooses not to invest since the energy price is less than user cost of capital plus fuel cost and carbon tax, $\frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F^1 = \frac{r + \delta_b}{a_b} + (\tilde{T} - \tilde{\tau}_b)F^1 + \pi + \tilde{\tau}_b F^1 > p_b$.

(I.b)–(I.c) As before.

(II.a) As before, let $r_b = r$, and we need to ensure that $I_b = 0 = I_b^*$, that is, $p_b \leq \frac{r + \delta_b}{a_b} + \tilde{\tau}_b F^1$. Choose any p_b that satisfies this condition.

(II.b) Choose r_g so that $K_g = K_g^*$, that is, $r_g = r - a_g(p^* - p_b)$.

(II.c) Given an actual energy price of p_b and carbon tax of $\tilde{\tau}_i f_i^1$, choose r_i such that goods producers behave as if their cost of energy is $\bar{p}_i = p_i^* = p^* + \tilde{T} f_i^1$ in terms of

their choice of energy intensity, labor, and investment. Now p_b is an equilibrium energy price since, at this price, the demand for energy, $\sum_i \epsilon_i Y_i = \sum_i \epsilon_i^* Y_i^*$, equals the supply, $a_g K_g + a_b \bar{K}_b = a_g K_g^* + a_b \bar{K}_b$.

(III.c) If we choose $r_i = r$, then goods producers must face a cost of energy of $\bar{p}_i = p_b + \tilde{\tau} f^1 = p^* + \tilde{T} f^1 = \bar{p}_i^*$, so we must ensure that $p_b = p^* + (\tilde{T} - \tilde{\tau}) f^1$.

(III.b) Choose r_g so that $K_g = K_g^*$, that is, $r_g = r - a_g(p^* - p_b) = r + (\tilde{T} - \tilde{\tau}) a_g f^1$.

(III.a) Letting $r_b = r + (\tilde{T} - \tilde{\tau}_b) a_b F^1 + (\tilde{T} - \tilde{\tau}) a_b f^1$ as before, the brown energy company optimally chooses not to invest since the energy price is less than user cost of capital plus fuel cost and carbon tax, $\frac{r_b + \delta_b}{a_b} + \pi + \tilde{\tau}_b F^1 = \frac{r + \delta_b}{a_b} + (\tilde{T} - \tilde{\tau}_b) F^1 + (\tilde{T} - \tilde{\tau}) f^1 + \pi + \tilde{\tau}_b F^1 > p^* + (\tilde{T} - \tilde{\tau}) f^1 = p_b$ using that $p^* < \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1$ from the proof of Proposition 1. $\square$

Proof of Proposition 5. The proof of Proposition 4 provides the cost of capital for brown and green energy firms, r_b and r_g , and shows that $p_b = p^*$. Turning to goods producing firms, clearly, each firm optimally commits to $\epsilon_i = \epsilon_i^*$ and $L_i = L_i^*$ given the extreme green finance scheme. Then what cost of capital r_i implements the socially optimal investment? To see that, we start by using (B.5) and inserting $\epsilon_i = \epsilon_i^* = \frac{s_i}{1+s_i} \frac{1}{p_i^*}$ into each firm's profit, so that (13) is replaced by

$$\Pi_i = \tilde{A}_i L_i^{\beta_i} K_i^{\alpha_i} - w L_i \quad (\text{B.9})$$

where the “productivity” based on this committed energy intensity is

$$\begin{aligned} \tilde{A}_i &= a_i \epsilon_i^{s_i} (1 - \bar{p}_i \epsilon_i) \\ &= a_i \left(\frac{s_i}{1+s_i} \frac{1}{p_i^*} \right)^{s_i} \left(1 - \frac{s_i}{1+s_i} \frac{\bar{p}_i}{p_i^*} \right) = a_i \left(\frac{s_i}{1+s_i} \frac{1}{p_i^*} \right)^{s_i} \frac{1 + s_i (1 - \frac{\bar{p}_i}{p_i^*})}{1 + s_i}, \end{aligned} \quad (\text{B.10})$$

which is larger than the social planner's A_i^* corresponding to $\bar{p}_i = p_i^*$. Therefore, when the firm chooses its capital based on (6)

$$\max_{K_i} \frac{\Pi_i - (r_i + \delta) K_i}{1 + r_i} = \frac{\tilde{A}_i L_i^{\beta_i} K_i^{\alpha_i} - w L_i - (r_i + \delta) K_i}{1 + r_i}, \quad (\text{B.11})$$

the solution increases in the “productivity” $\tilde{A}_i$

$$K_i = \left(\frac{\alpha_i \tilde{A}_i L_i^{\beta_i}}{r_i + \delta} \right)^{\frac{1}{1-\alpha_i}} \quad (\text{B.12})$$

So, to get the same answer with r_i and $\tilde{A}_i$ as that of the social planner's first-order condition with respect to K_i at the social optimum, corresponding to r and A_i^* , we need

$$\frac{\bar{r}_i + \delta}{r + \delta} = \frac{\tilde{A}_i}{A_i^*} = 1 + s_i \left(1 - \frac{\bar{p}_i}{p_i^*}\right) = 1 + s_i \frac{p_i^* - \bar{p}_i}{p_i^*} = 1 + s_i \frac{(\tilde{T} - \tilde{\tau}_i) f_i^1}{p^* + \tilde{T} f_i^1}. \quad (\text{B.13})$$

using that $\bar{p}_i = p_b + \tilde{\tau}_i f_i^1 = p^* + \tilde{\tau}_i f_i^1$ and $p_i^* = p^* + \tilde{T} f_i^1$. Therefore,

$$\bar{r}_i = (r + \delta) \left(1 + s_i \frac{(\tilde{T} - \tilde{\tau}_i) f_i^1}{p^* + \tilde{T} f_i^1}\right) - \delta = r + \frac{s_i (\tilde{T} - \tilde{\tau}_i) f_i^1 (r + \delta_b)}{p^* + \tilde{T} f_i^1}. \quad (\text{B.14})$$

When $I_b^* > 0$, it further holds that $p^* = \frac{r + \delta_b}{a_b} + \pi + \tilde{T} F^1$. □

Proof of Proposition 6. With green finance of the form $r_i(\epsilon_i)$, the firm must choose its carbon intensity ϵ_i and capital K_i to maximize NPV, taking discount rate effects into account:

$$\max_{\epsilon_i, K_i} \frac{\Pi_i(\epsilon_i, K_i) + (1 - \delta) K_i}{1 + r_i(\epsilon_i)} - K_i = \frac{a_i \epsilon_i^{s_i} (1 - \bar{p}_i \epsilon_i) K_i^{\alpha_i} + (1 - \delta) K_i}{1 + r_i(\epsilon_i)} - K_i \quad (\text{B.15})$$

The first-order condition with respect to ϵ_i is

$$0 = a_i (s_i \epsilon_i^{s_i-1} - \bar{p}_i (s_i + 1) \epsilon_i^{s_i}) K_i^{\alpha_i} (1 + r_i(\epsilon_i)) - r'_i(\epsilon_i) [a_i \epsilon_i^{s_i} (1 - \bar{p}_i \epsilon_i) K_i^{\alpha_i} + (1 - \delta) K_i]$$

that is

$$\begin{aligned} r'_i(\epsilon_i) &= (1 + r_i(\epsilon_i)) \frac{a_i (s_i \epsilon_i^{s_i-1} - \bar{p}_i (s_i + 1) \epsilon_i^{s_i}) K_i^{\alpha_i}}{a_i \epsilon_i^{s_i} (1 - \bar{p}_i \epsilon_i) K_i^{\alpha_i} + (1 - \delta) K_i} \\ &= (1 + r_i(\epsilon_i)) \frac{s_i \epsilon_i^{-1} - \bar{p}_i (s_i + 1)}{1 - \bar{p}_i \epsilon_i + \frac{1 - \delta}{a_i} K_i^{1 - \alpha_i} \epsilon_i^{-s_i}} \end{aligned}$$

Evaluating this at $\epsilon_i^* = \frac{s_i}{1 + s_i} \frac{1}{p_i^*}$ from (B.5) and using that

$$\frac{1 - \delta}{a_i} (K_i^*)^{1 - \alpha_i} (\epsilon_i^*)^{-s_i} = \frac{\alpha_i (1 - \delta)}{(1 + s_i)(r + \delta)} \quad (\text{B.16})$$

we have the condition

$$\begin{aligned}
r'_i(\epsilon_i^*) &= (1 + \bar{r}_i) \frac{(p_i^* - \bar{p}_i)(1 + s_i)}{1 - \frac{s_i}{1+s_i} \frac{\bar{p}_i}{p_i^*} + \frac{\alpha_i(1-\delta)}{(1+s_i)(r+\delta)}} \\
&= (1 + \bar{r}_i) \frac{(1 + s_i)^2 (p_i^* - \bar{p}_i)}{\frac{\bar{r}_i + \delta + \alpha_i(1-\delta)}{r+\delta}} \\
&= (1 + \bar{r}_i) \frac{(r + \delta)(1 + s_i)^2 (p_i^* - \bar{p}_i)}{\bar{r}_i + \delta + \alpha_i(1 - \delta)} \\
&= (1 + \bar{r}_i) \frac{(r + \delta)(1 + s_i)^2 (\tilde{T} - \tilde{\tau}_i) f_i^1}{\bar{r}_i + \delta + \alpha_i(1 - \delta)}
\end{aligned}$$

We see that this condition is satisfied at ϵ_i^* when the cost of capital is given by (26). Further, the first order condition for K_i is satisfied at the social optimum, as seen from the proof of Proposition 5. $\square$

Proof of Proposition 7. The proof of Proposition 4 provides the cost of capital for brown and green energy firms, r_b and r_g , and shows that $p_b < p^*$.

Based on the same arguments as in the proofs of Propositions 5–6, we see that

$$\begin{aligned}
\bar{r}_i &= (r + \delta_b) \frac{\tilde{A}_i}{A_i^*} - \delta_b = (r + \delta_b) \left(1 + s_i \frac{p_i^* - \bar{p}_i}{p_i^*} \right) - \delta_b \\
&= (r + \delta_b) \left(1 + s_i \frac{p^* - p_b + (\tilde{T} - \tilde{\tau}_i) f_i^1}{p^* + \tilde{T} f_i^1} \right) - \delta_b \\
&= r + (r + \delta_b) s_i \frac{p^* - p_b + (\tilde{T} - \tilde{\tau}_i) f_i^1}{p^* + \tilde{T} f_i^1}
\end{aligned} \tag{B.17}$$

using that $\bar{p}_i = p_b + \tilde{\tau}_i f_i^1 < p^* + \tilde{\tau}_i f_i^1$ and $p_i^* = p^* + \tilde{T} f_i^1$. When the constraint $I_b \geq 0$ is not binding, we have $p^* = \frac{r+\delta_b}{a_b} + \pi + \tilde{T} F^1$ and $p_b = \frac{r+\delta_b}{a_b} + \pi + \tilde{\tau}_b F^1$ so

$$\bar{r}_i = r + (r + \delta_b) s_i \frac{(\tilde{T} - \tilde{\tau}_i) f_i^1 + F^1 (\tilde{T} - \tilde{\tau}_b)}{\frac{r+\delta_b}{a_b} + \pi + \tilde{T} (f_i^1 + F^1)}. \tag{B.18}$$

$\square$

Proof of Proposition 8. The proof of Proposition 4 provides the cost of capital for brown and green energy firms, r_b and r_g , and shows that $r_i = r$ for goods producers. $\square$

Proof of Proposition 9. Consider the socially optimal equilibrium from Proposition 1 and define $\bar{C}$ as the associated total emission, $\bar{C} = \sum_i (\epsilon_i Y_i - \sum_{q \geq \bar{q}_i} o_{i,q})$. Then the equilibrium

with traded carbon allowances is the same as the equilibrium with a carbon tax of T and the equilibrium carbon allowance price is $\tau = T$. Indeed, given the same wage and offset prices, each firm chooses the same $(\epsilon_i, o_{iq}, L_i, K_i, I_i)$ to maximize their value, offset producers maximize profits at the same quantities, and workers supply the same amount of labor to maximize their utility. $\square$