Sustainable finance under regulation*

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Abstract

We study how sustainable investing interacts with environmental regulation. Green investors are willing to sacrifice returns to invest in cleaner firms, partly substituting for policy, but they do not internalize the full social cost of emissions, so regulation remains necessary. Standard tools such as pollution taxes shrink dirty firms but also reshape their shareholder bases: the most pollution-averse investors exit first, leaving behind shareholders less willing to sacrifice financial returns for pollution reduction. This shareholder-base effect weakens dirty firms' incentives to adopt green technology. Consequently, tighter environmental regulation can increase pollution, and optimal policy may depart from the Pigouvian benchmark.

Keywords: Environmental regulation, socially responsible investment, pollution externality, shareholder composition

JEL: G11, G23, G32, H23, H41, Q58, M14

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1 Introduction

It is well acknowledged that human activities contribute to climate change and, hence, firms need to reduce their emissions to mitigate it (e.g., IPCC, 2018). In response to this challenge, there has been a dramatic increase in socially responsible investing in financial markets (e.g., GSIA, 2021). However, emissions are externalities, and so investors alone are unlikely to fully resolve this issue. Therefore, government interventions remain necessary. In fact, in recent years the number and the scope of environmental regulations have been growing worldwide (e.g., World Bank, 2025). The coexistence of the private approach (through sustainable investing) and the public approach (through environmental policies) to address climate change raises fundamentally important questions: How do socially concerned investors respond to environmental regulations? What is the optimal regulation in the presence of such investors?

In this paper, we analyze the interaction between sustainable investing and environmental regulation. In our model, sustainable investing partially substitutes for regulation because investors with green preferences are willing to sacrifice financial returns to invest in cleaner firms. However, regulation remains necessary because investors do not fully internalize the social cost of emissions. Conventional wisdom suggests that environmental regulations, such as pollution taxes, reduce emissions by shrinking polluting firms and incentivizing the adoption of cleaner technologies. We show that this logic can break down in the presence of sustainable investors. Our key insight is that sustainable investing changes how regulation operates: by reshaping firms' shareholder bases, standard policy tools can weaken clean technology adoption incentives and increase pollution.

We consider an economy populated with heterogeneous investors and firms. There are two firm types. Firms of the c-type are less productive but clean, while d-firms are initially equipped with a brown technology but can adopt a cleaner green technology at a cost. Pollution is an externality that negatively affects all investors. Since all agents are atomistic, they do not internalize their effect on the aggregate pollution.

In addition to being adversely affected by the externality, investors have heteroge-

neous green preferences. In particular, they incur varying degrees of disutility from holding shares of polluting firms. Such preferences may be driven by a nonpecuniary warm-glow disutility from being associated with polluting firms (Andreoni, 1990). Investors with strong green preferences may also be managers of ESG funds, whose compensation and reputation hinge on identifying sustainable firms.[1]

We start by analyzing investors' capital allocation and firms' adoption decisions in the laissez-faire economy. Capital allocation is characterized by a threshold in the strength of green preferences. For a marginal investor, the financial advantage of d-firms and the disutility caused by their higher pollution are exactly balanced. Investors with above-threshold green preferences acquire shares of clean but less financially attractive c-firms, while the remaining investors acquire shares of d-firms.

As a result, d-firms' capital is limited to wealth of investors with below-threshold green preferences. Crucially, the composition of a firm's shareholder base also shapes its decision to adopt the green technology. Specifically, a d-firm adopts the green technology if the average shareholder's green preference is sufficiently strong to justify incurring the adoption cost. There are no conflicts of interest between shareholders and managers: managers maximize average shareholder utility when deciding whether to adopt the green technology, taking aggregate pollution as given.

Two symmetric equilibria are possible in this environment. In the *brown* equilibrium, a marginal investor has weak green preferences, which implies that the shareholder base of d-firms consists of investors who care primarily about firms' financial performance. In this equilibrium, d-firms do not adopt the green technology. Expecting d-firms to pollute intensively, even investors with moderate green preferences do not invest in them. In the *green* equilibrium, d-firms' shareholders have sufficiently strong green preferences to support the green technology adoption. Expecting d-firms to pollute less intensively, investors with moderate green preferences invest in them.

The green equilibrium exists only if the relative financial advantage of d-firms is

[1]See Crumpler and Grossman (2008), Bonnefon, Landier, Sastry, and Thesmar (2019), and Heeb, Kölbel, Paetzold, and Zeisberger (2022) for evidence on warm-glow preferences. Hartzmark and Sussman (2019) document that mutual funds ranked highly in sustainability by Morningstar attract additional flows.

sufficiently large. Intuitively, a high financial benefit is needed to incentivize investors with strong green preferences to invest in d-firms. Such investors, in turn, make d-firms' shareholder base sufficiently pro-green to adopt the green technology. In contrast, the brown equilibrium exists only if the relative financial advantage of d-firms is not too large. We further show that the two equilibria coexist if the difference in financial performances between c- and d-firms is moderate.

It follows that even in the absence of regulation, sustainable investing alleviates the pollution externality, despite investors being atomistic and failing to internalize the effect of their actions on aggregate pollution. If investors did not incur any disutility from holding polluting shares, only more financially attractive d-firms would receive funding, and these firms would never adopt the green technology. The presence of investors with green preferences both reduces the size of d-firms and, if the green equilibrium exists and is played, induces these firms to adopt the green technology.

However, since investors do not internalize their impact on aggregate pollution, the laissez-faire economy features too high pollution, and so there is scope for regulation. To clearly show that, we develop an efficient benchmark in which the planner controls capital allocation and d-firms' adoption decisions without having to consider the preferences of d-firms' shareholders. If adoption costs are not too high, the planner prefers d-firms to adopt the green technology while keeping them smaller than in the green laissez-faire equilibrium. A natural way to reduce the size of polluting firms in the decentralized economy is through a pollution tax, and we therefore analyze the effects of this policy instrument next.

The pollution tax has two effects on the economy. First, it reduces the size of d-firms. Because they pollute in any equilibrium, a higher tax makes them less financially attractive and so implies a reallocation of capital toward c-firms. The aggregate pollution is then lower in any equilibrium. Second, d-firms' incentives to adopt the green technology change. Naturally, a higher tax implies that it is more financially costly to operate the brown technology. On the other hand, the tax also reshapes firms' shareholder bases. As

the financial advantage of d-firms diminishes with the tax, pro-green shareholders of these firms switch to become shareholders of c-firms. This shareholder-base effect implies that d-firms' shareholders become less pro-green, and so are less willing to adopt the green technology. If the shareholder-base effect is strong, a higher tax can therefore make the green equilibrium non-existent.

This result has direct implications for optimal taxation. When the externality is sufficiently weak or strong, a pollution tax alone can implement the efficient allocation.[2] The interesting case arises when the externality is of intermediate strength. In this case, the tax required to achieve the efficient reduction in the size of d-firms weakens support for adoption and can eliminate the green equilibrium, thus making the efficient allocation unattainable. The optimal tax therefore deviates from the Pigouvian benchmark. It is optimal either to under-correct the externality, keeping d-firms larger than in the efficient allocation but preserving a sufficiently green shareholder base to sustain adoption, or to over-correct it, making d-firms inefficiently small but providing strong financial incentives for adoption. Naturally, under-correction is optimal when the externality is relatively weaker, while over-correction is optimal when it is relatively stronger.

The mechanism through which a higher tax can weaken support for green technology adoption—and thus cause the optimal tax to deviate from the Pigouvian benchmark—is the endogenous shareholder-base effect. When this effect is strong, a tax increase can backfire and raise pollution. Its strength depends on the distribution of green preferences in the investor population. In particular, the effect is strong when the investor base is *balanced* yet *polarized*, meaning that d-firms are held by comparable masses of investors with sharply divergent green preferences. In this case, even a small tax increase induces a large exit of investors with strong green preferences from d-firms, leaving them with shareholders whose green preferences are substantially weaker. In contrast, when d-firms' shareholder base is dominated by a single investor group, or preferences of shareholders are fairly uniform, the shareholder-base effect is weak. In that case, a higher tax strengthens

[2] If the externality is very weak, the optimal tax is low and does not materially distort adoption incentives. If the externality is very strong, the optimal tax is high, making non-adoption prohibitively costly and inducing adoption even with a weakly pro-green shareholder base.

adoption incentives, in line with the conventional wisdom.

While a pollution tax alone is generally insufficient to implement the efficient allocation, the regulator can attain the efficient allocation with two policy instruments—for example, a pollution tax combined with a firm-type-specific subsidy. Setting the tax at a sufficiently high level induces green technology adoption but typically makes d-firms inefficiently small. An unconditional subsidy to d-firms then restores their efficient size.[3]

Overall, our theory shows that environmental regulation must be rethought in the presence of sustainable investors. On the one hand, sustainable investing partially substitutes for regulation by reducing the size of polluting firms and inducing the adoption of green technologies. On the other hand, regulation remains necessary to fully internalize the pollution externality. Crucially, however, conventional policy tools such as a pollution tax can backfire in this environment. By imposing financial costs on polluting firms, these policies reshape firms' shareholder bases. As the most pro-green investors exit first, polluting firms are left with shareholders who have weaker green preferences, which in turn undermines incentives to adopt clean technologies. More broadly, this mechanism echoes a large literature on unintended consequences of environmental policy, such as carbon leakage (OECD, 2020), rebound effects (Jevons, 1866), increased market concentration (Ryan, 2012), regressive distributional effects (Fullerton, 2017), or tightening of financial constraints (Döttling and Rola-Janicka, 2025). Relatedly, stronger green preferences can lead to higher pollution for a given level of regulation, which relates our paper to work on the unintended consequences of sustainable investing.[4]

[3]We also show that a subsidy alone is not sufficient to implement the efficient allocation and discuss alternative policy instruments that, when combined with the tax, can achieve the efficient allocation.

[4]In particular, sustainable investing can lead to a weaker managerial support for the intended action (Davies and Van Wesep, 2018), product market concentration (Bisceglia, Piccolo, and Schneemeier, 2022), green technology adoption delays (Gupta, Kopytov, and Starmans, 2026), worse price informativeness (Goldstein, Kopytov, Shen, and Xiang, 2022; Chen, Starmans, and Gupta, 2024), or political backlash against environmental policies (Carlson, Fisher, and Lazrak, 2022; Allen, Barbalau, and Zeni, 2023; Döttling, Levit, Malenko, and Rola-Janicka, 2024). Also related are papers emphasizing how sustainable preferences can be counterproductive in the governance context (Malenko and Malenko, 2023; Geelen, Hajda, and Starmans, 2024; Bond and Levit, 2025).

Literature Our paper contributes to the theoretical literature on environmental regulation (see Nordhaus (2014) for a comprehensive discussion). The paper's novel feature is a shareholder-base effect through which regulation shapes firms' incentives to reduce pollution. Most related to our paper are models studying environmental regulation in the presence of investors with green preferences. Baker, Hollifield, and Osambela (2020) and Moisson (2020) consider firms with pre-determined technologies and study the effects of Pigouvian taxation on investors' portfolio decisions. In contrast, in our model, green technology adoption decisions are endogenous. Acemoglu and Rafey (2019) and Biais and Landier (2022) analyze green technology development and adoption under environmental regulations when the regulator lacks commitment power. Hong, Wang, and Yang (2023) and Gupta et al. (2026) study welfare-maximizing socially responsible investing mandates. Inderst and Opp (2025) analyze optimal sustainability labeling when investors value labeled assets. Döttling and Rola-Janicka (2025) analyze how socially responsible investing affects firms' financial constraints and study optimal environmental and financial regulations in this environment. Pedersen (forthcoming) quantifies the extent to which green finance can substitute for carbon pricing.[5]

A large literature examines how portfolio decisions are affected by investors' sustainability preferences. A common feature of this literature is that sustainable investors overweight green firms in their portfolios, reducing their cost of capital. Green firms then invest more, while brown firms have incentives to adopt cleaner technologies, expecting to benefit from a lower cost of capital later (Heinkel, Kraus, and Zechner, 2001; Friedman and Heinle, 2016; Pástor, Stambaugh, and Taylor, 2021; De Angelis, Tankov, and Zerbib, 2022).[6] A related literature studies the clientele and catering effects, where firms cater to shareholders' tastes for investment (Aghion and Stein, 2008; Polk and Sapienza, 2009),

[5]In settings featuring investors with no green preferences, Hoffmann, Inderst, and Moslener (2017) and Heider and Inderst (2021) analyze environmental regulations when firms face financing frictions; Dávila and Walther (2021) and Oehmke and Opp (2022) study financial regulations such as green capital requirements aimed at mitigating financial risks and environmental externalities.

[6]These papers also study asset pricing implications; other studies focusing on asset pricing in the presence of socially concerned investors are Fama and French (2007); Luo and Balvers (2017); Pedersen, Fitzgibbons, and Pomorski (2021); Zerbib (2022). Piatti, Shapiro, and Wang (2022) study asset pricing and public good provision in the portfolio-choice model featuring large socially-concerned and financial investors.

dividends (Allen, Bernardo, and Welch, 2000; Baker and Wurgler, 2004), nominal stock prices (Baker, Greenwood, and Wurgler, 2009), or political preferences (Wu and Zechner, 2024). In contrast, in our model, firms make decisions based on the preferences of their ultimate shareholders. As a result, firms owned by investors with weak green preferences do not adopt the green technology, even if committing to adopt it ex ante would attract sustainable capital and increase their ex-ante share price.

The feedback between shareholder composition and corporate policy is a common feature of models with heterogeneous investors who trade before firms choose their policies. Levit, Malenko, and Maug (2024) analyze complementarity between trading and subsequent voting in a one-firm setting with atomistic investors. Levit, Malenko, and Maug (forthcoming) show how voting premium emerges in a similar setting with a blockholder. Gollier and Pouget (2022) consider firms with pre-established assets and study secondary-market trading. In a contemporaneous paper, Bisceglia et al. (2022) show that secondary-market trading can lead to a concentration of responsible capital, crowding out abatement efforts in excluded firms and increasing markups for green products. The feedback loop between portfolio allocations and firms' decisions in our model is related to the mechanisms studied in these papers.[7] There are, however, important differences. First, we focus on environmental regulation and its interaction with this feedback loop. Second, we consider primary markets, so that portfolio allocations determine not only shareholder bases but also firm size. This distinction is crucial for the regulator's tradeoff between reducing the size of polluting firms and keeping their shareholder composition sufficiently pro-green. Finally, we characterize how the shape of the distribution of investor preferences affects the strength of the shareholder-base effect.

Our model emphasizes a tension between the exit and voice channels of sustainable investing. Broccardo, Hart, and Zingales (2022) and Jagannathan, Kim, McDonald, and Xia (2022) compare the effectiveness of exit and voice strategies in inducing firms to re-

[7] A somewhat related feedback arises in Aghion and Stein (2008), where a firm manager can exert effort to increase sales growth or to improve profit margins. If the market conjectures that the firm is pursuing a growth strategy, it places more weight on sales performance when inferring managerial ability, which rewards the manager for pursuing a growth strategy and thereby reinforces the market's original belief.

duce negative externalities, but they consider the two strategies separately. Our focus is instead on the endogenous interaction between exit and voice: policy-driven divestment shifts ownership toward investors with weak green preferences, undermining green technology adoption ex post.[8] More broadly, this relates to the classic corporate governance question of how effective exit and voice strategies are in addressing the shareholder-manager agency problem (see Edmans and Holderness (2017) for a review). In this literature, shareholders typically share a common financial objective but may differ in their information. In contrast, we consider investors with heterogeneous preferences and common information sets, and abstract away from agency frictions. Some papers in this literature also study endogenous ownership structure (notably, Kahn and Winton, 1998; Maug, 1998; Edmans and Manso, 2011), but the focus is typically on the number of blockholders rather than on the distribution of shareholders' preferences. Another difference is that we focus on atomistic investors, whereas this literature considers blockholders who behave strategically and internalize their impact on corporate actions.[9]

2 Model setting

The economy is populated with a continuum of investors who differ in the strength of green preferences and a continuum of firms of two types, $i \in \{c, d\}$. Firms of c-type are less productive but never pollute. Firms of d-type start with a polluting brown technology but can reduce their pollution intensity by adopting a costly green technology. There are two periods, $t = 1, 2$, and no time discounting. All agents are atomistic and risk-neutral. At $t = 1$, investors finance firms by acquiring firms' shares. At $t = 2$, d-firms' managers choose whether to adopt the green technology. Firms then produce, investors consume firms' cash flows, and potentially suffer from a pollution externality.

[8] In a model with a financial-market governance channel, Chen et al. (2024) show that exit and voice strategies can be complementary.

[9] Relatedly, a number of papers in the sustainable finance literature consider engagement by large impact investors on externalities generated by firms (e.g., Chowdhry, Davies, and Waters (2019); Morgan and Tumlinson (2019); Oehmke and Opp (2020); Green and Roth (2021); Gollier and Pouget (2022); Edmans, Levit, and Schneemeier (2022); Landier and Lovo (2020); Gupta et al. (2026)).

2.1 Production technology

Since firms of the same type appear identical to shareholders, we focus on symmetric equilibria in which all firms of the same type receive identical funding and have identical shareholder bases.[10] Each c-firm raises capital k_c from investors and produces the final good using a linear production technology, $y_c = \alpha_c k_c$. None of c-firms pollute.

Each d-firm raises capital k_d and produces the final good using a linear production technology, $y_d = k_d\left(\alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}}\right)$, where $\mathsf{a}_d \in \{0,1\}$ indicates if a d-firm adopts the green technology. If the brown technology is operated, $\mathsf{a}_d = 0$, the firm does not incur any adoption costs but generates k_d units of public bad, which we refer to as pollution. If a d-firm operates the green technology, $\mathsf{a}_d = 1$, it incurs a proportional cost $f > 0$ that captures any expenses to install new equipment and change the production process. In that case, it produces πk_d units of pollution, where $\pi \in (0,1)$.[11]

The key to our results are two differences between c- and d-firms: d-firms are more productive, $\Delta \equiv \alpha_d - \alpha_c > 0$, but are more polluting. To keep the analysis transparent, we assume that c-firms never pollute or, equivalently, face zero cost of eliminating pollution. There are several ways to think about firms of different types in our model. For example, c-firms can be thought of as firms that are committed to significant investments in the research and development of clean technologies. While their financial performances can be weakened because of that, they are also likely to develop an in-house clean technology. In contrast, d-firms do not spend much on R&D, which is attractive financially but makes the green technology adoption costlier. In particular, such firms may rely more on buying expensive patents developed by other firms. One may also think about c- and d-firms as using inherently different ways to produce. For example, c-firms can be thought of as firms producing energy using renewable technologies, such as wind and solar. In contrast, d-firms operate well-developed but more polluting fossil fuel-based technologies. Reducing

[10] There can exist an equilibrium in which d-firms have different shareholder bases and make different green technology adoption decisions. Such an equilibrium, however, requires investors to condition their actions on firms' identities rather than on payoff-relevant characteristics. We therefore focus on anonymous symmetric equilibria.

[11] We consider other adoption cost functions in Online Appendix C.6.

their carbon footprints, e.g., through carbon capture, is expensive for d-firms and unlikely to entirely eliminate their pollution.

2.2 Investor preferences and portfolio choice

There is a unit mass of heterogeneous atomistic investors. All investors are endowed with the same initial wealth, normalized to one without loss of generality. Investors differ in their attitudes toward holding shares of polluting firms in their portfolios. Specifically, an investor γ holding s_d^γ shares of a d-firm incurs a nonpecuniary disutility $s_d^\gamma \times \gamma k_d \left(\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}\right)$, where the total amount of shares issued by each firm is normalized to one. Investors do not incur any nonpecuniary disutility from holding shares of nonpolluting c-firms. The cumulative distribution function and the probability density function of γ in the investor population are $G(\cdot)$ and $g(\cdot)$, respectively, and the support is $[0, \bar{\gamma}]$, where $\bar{\gamma} > 0$. We assume that $G(\cdot)$ is an increasing continuous function on $[0, \bar{\gamma}]$ and that it is differentiable on $(0, \bar{\gamma})$.

When making their portfolio decisions at $t = 1$, investors form expectations about d-firms' adoption decisions, i.e., if $\mathsf{a}_d = 0$ or $\mathsf{a}_d = 1$. From the perspective of an investor γ, the values of investing one dollar in a c-firm and a d-firm are, respectively,

$$v_c = \alpha_c \quad \text{and} \quad v_d\left(\gamma, \mathsf{a}_d\right) = \alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}} - \gamma\left(\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}\right). \tag{1}$$

The portfolio choice problem of this investor is

$$\max_{\{s_i^\gamma\}} \sum_{i\in\{c,d\}} s_i^\gamma k_i v_i + \left(1 - \sum_{i\in\{c,d\}} s_i^\gamma p_i\right) R - \varepsilon\xi(P), \ \text{ s.t.} \sum_{i\in\{c,d\}} s_i^\gamma p_i \leq 1, \ \text{and } s_i^\gamma \geq 0 \ \forall i, \tag{2}$$

where p_i is the share price of type-i firms and R is the risk-free rate. The constraints restrict borrowing and short-selling.[12] The term $\varepsilon\xi\left(P\right)$ reflects the externality due to aggregate pollution $P = K_d\left(\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}\right)$, where $\varepsilon \geq 0$ is the externality strength and K_d is the total wealth invested in d-firms. We assume that $\xi(\cdot)$ is a strictly increasing

[12] Online Appendix C.1 shows that imposing the no-borrowing constraint is without loss of generality. Since our focus is on firms raising funds, the absence of short selling is natural. An interesting question is whether investors with positive green preferences ($\gamma > 0$) would derive utility from shorting polluting stocks. To the best of our knowledge, there is no existing evidence on this issue.

and convex function such that $\xi(0) = \xi'(0) = 0$. As we focus on atomistic investors and firms, all economic agents take the aggregate pollution as given.

We assume that each firm issues a unit mass of shares so that the market clearing implies $\int s_i^\gamma dG(\gamma) = 1$. As a result, the amount of capital each type-i firm raises is $k_i = p_i \int s_i^\gamma dG(\gamma) = p_i$. We also assume that bonds are in zero net supply. Therefore, the risk-free rate R is endogenously determined such that none of the investors is willing to save via bonds, and so the constraint $\sum_{i\in\{c,d\}} s_i^\gamma p_i \leq 1$ holds as equality for all investors.[13]

From (2), it then follows that an investor γ invests all her wealth in shares of type-i firms with the highest v_i. From (1), the value per dollar invested in a c-firm, v_c, does not depend on γ, and the value per dollar invested in a d-firm, v_d, decreases in γ because $\pi > 0$. Therefore, investor wealth allocation follows a simple threshold rule.

Lemma 1. *There exists a threshold $\hat{\gamma}$ such that investors with $\gamma < \hat{\gamma}$ (if any) invest all their wealth in d-firms and investors with $\gamma > \hat{\gamma}$ (if any) invest all their wealth in c-firms. In particular, for investors with $\gamma < \hat{\gamma}$, $s_c^\gamma = 0$ and $s_d^\gamma = 1/G(\hat{\gamma})$, and for investors with $\gamma > \hat{\gamma}$, $s_c^\gamma = 1/(1 - G(\hat{\gamma}))$ and $s_d^\gamma = 0$. The mass of investors who are indifferent between investing in c- and d-firms is zero.*[14]

Proof. See Appendix A.1. □

2.3 Green technology adoption

At $t = 2$, after investors have chosen their portfolios and shareholder bases have been formed, managers of d-firms choose whether to adopt the green technology. We abstract away from agency frictions, such that a manager of a d-firm adopts the green technology if and only if the adoption reduces the average nonpecuniary disutility of its shareholders by at least as much as the adoption cost. As discussed above, since all agents and firms are atomistic, d-firms' managers do not take into account that operating the

[13] Since borrowing is ruled out and risk-free bonds are in zero net supply, investors hold no risk-free assets in equilibrium. To guarantee that, R must not exceed α_c, but the exact value of R is not pinned down. See also Online Appendix C.1 where we allow investors to borrow.

[14] In Online Appendix C.8, we explore a model in which investors have hedging motives. In that case, investors have incentives to diversify and hold firms of both types. We show, however, that the key economic forces remain the same as in the risk-neutral model.

brown technology contributes more to the aggregate pollution. From Lemma 1, a d-firm adopts the green technology if and only if

$$\underbrace{fG\left(\hat{\gamma}\right)+\pi\int_{0}^{\hat{\gamma}}\gamma dG(\gamma)}_{\text{Cost of adopting}}\leq\underbrace{\int_{0}^{\hat{\gamma}}\gamma dG(\gamma)}_{\text{Cost of not adopting}}\Leftrightarrow\psi\left(\hat{\gamma}\right)\equiv\frac{\int_{0}^{\hat{\gamma}}\gamma dG(\gamma)}{G(\hat{\gamma})}\geq\frac{f}{1-\pi}. \tag{3}$$

The left-hand side of the inequality (3) contains two terms. The first term, $fG(\hat{\gamma})$, is the monetary cost of adopting the green technology. The second term, $\pi\int_{0}^{\hat{\gamma}}\gamma dG\left(\gamma\right)$, is the total nonpecuniary disutility to shareholders of a d-firm when it reduces its pollution intensity to $\pi<1$. The right-hand side, $\int_{0}^{\hat{\gamma}}\gamma dG(\gamma)$, is the nonpecuniary disutility to shareholders of a d-firm when it does not adopt the green technology and therefore pollutes intensively. Inequality (3) makes clear that a d-firm adopts the green technology if and only if its average shareholder prefers it to do so.

No-green-preference benchmark Before proceeding to the equilibrium characterization, it is useful to briefly discuss the benchmark economy in which investors have no green preferences, i.e., $\gamma=0$ for all investors. In this case, all investors allocate their wealth to the more financially productive d-firms, so that $K_d=1$ and $K_c=0$. Furthermore, d-firms never adopt the green technology, since (3) is never satisfied. Consequently, the aggregate output and the aggregate pollution are, respectively,

$$Y_0=\alpha_d\quad\text{and}\quad P_0=1. \tag{4}$$

This benchmark serves as a useful reference point for our subsequent analysis of the main model in which investors have green preferences.

3 Equilibrium characterization

Lemma 1 characterizes how investors allocate their wealth across firms given their expectations about d-firms' adoption decisions. Investors' wealth allocation shapes firms' shareholder composition, which, in turn, determines their adoption decisions, as characterized by expression (3). In equilibrium, investors' portfolio choices and firms' adoption

decisions are jointly determined. We characterize the equilibria in Sections 3.1 and 3.2. In Section 3.3, we argue that in the laissez-faire economy, capital allocation and adoption decisions are efficient if the pollution externality is absent (i.e., if $\varepsilon = 0$). The presence of the externality calls for regulation, which we analyze in Section 4.

3.1 Brown and green equilibria

Two symmetric equilibria arise in our model: a brown equilibrium, in which d-firms do not adopt the green technology, $\mathsf{a}_d = 0$, and a green equilibrium, in which d-firms adopt the green technology, $\mathsf{a}_d = 1$.[15]

Brown equilibrium: $\mathsf{a}_d = 0$ In this equilibrium, d-firms do not adopt the green technology. From (1), we have $v_d(\gamma, 0) = \alpha_d - \gamma$, and so investors with $\gamma \in [0, \hat{\gamma}_b)$ invest in d-firms and investors with $\gamma \in [\hat{\gamma}_b, \bar{\gamma}]$ invest in c-firms, where $\hat{\gamma}_b$ is determined by

$$v_c = v_d\left(\hat{\gamma}_b, 0\right) \Leftrightarrow \hat{\gamma}_b = \Delta. \tag{5}$$

Clearly, d-firms always raise nonzero capital in this equilibrium because $\Delta > 0$. Furthermore, if $\hat{\gamma}_b < \bar{\gamma}$, then c-firms also raise nonzero capital in this equilibrium.

To verify that this is an equilibrium, we need to check that d-firms do not adopt the green technology. From (3), this is indeed the case if

$$\psi\left(\hat{\gamma}_b\right) = \frac{\int_0^{\hat{\gamma}_b} \gamma dG(\gamma)}{G\left(\hat{\gamma}_b\right)} < \frac{f}{1-\pi}. \tag{6}$$

Clearly, as $\hat{\gamma}_b$ decreases, shareholders of d-firms become, on average, less concerned about the greenness of their portfolios. Consequently, they are less willing to sacrifice financial performance for the green technology adoption (the left-hand side of (6) goes down), and (6) is more likely to be satisfied. By definition of $\hat{\gamma}_b$, given in (5), this happens if d-firms become less financially attractive relative to c-firms, i.e., Δ shrinks. Intuitively, if the financial benefit from investing in polluting d-firms is small, high-γ investors are not

[15] An investor is indifferent between all c-firms and all d-firms that make identical adoption decisions. Therefore, there exist infinite equilibria featuring the same aggregate quantities and adoption decisions by d-firms but different shareholder bases. To rule out this multiplicity, we assume if investors are indifferent across investing in several firms, they hold an equal-weighted portfolio of all such firms.

willing to invest in them. As a result, the brown equilibrium exists if d-firms' financial advantage is not too high and their shareholder bases consist of low-γ investors. We formalize this result in Proposition 1 below.

To complete the description of the brown equilibrium, we compute several aggregate quantities. The amounts of capital raised by d- and c-firms are, respectively, $G(\hat{\gamma}_b)$ and $1-G(\hat{\gamma}_b)$.[16] Using those, we can easily compute output Y_b, pollution P_b, and welfare W_b:

$$Y_b = \alpha_c (1 - G(\hat{\gamma}_b)) + \alpha_d G(\hat{\gamma}_b), \; P_b = G(\hat{\gamma}_b), \text{ and } W_b = Y_b - \int_0^{\hat{\gamma}_b} \gamma dG(\gamma) - \varepsilon \xi(P_b). \quad (7)$$

Welfare W_b aggregates investors' utilities and equals the total output net of the aggregate nonpecuniary disutility of d-firms' shareholders and the pollution externality.

Green equilibrium, $\mathsf{a}_d = 1$ In this equilibrium, d-firms adopt the green technology. From (1), we have $v_d(\gamma, 1) = \alpha_d - f - \pi\gamma$, and so investors with $\gamma \in [0, \hat{\gamma}_g)$ invest in d-firms and investors with $\gamma \in [\hat{\gamma}_g, \bar{\gamma}]$ invest in c-firms, where $\hat{\gamma}_g$ is determined by

$$v_c = v_d(\hat{\gamma}_g, 1) \Leftrightarrow \hat{\gamma}_g = \frac{\Delta - f}{\pi}. \quad (8)$$

In this equilibrium, d-firms raise nonzero capital as long as $\hat{\gamma}_g > 0$, i.e., if $\Delta > f$, and c-firms raise nonzero capital if $\hat{\gamma}_g < \bar{\gamma}$.

To verify that this is an equilibrium, we need to check that d-firms adopt the green technology. From (3), this is indeed the case if

$$\psi(\hat{\gamma}_g) = \frac{\int_0^{\hat{\gamma}_g} \gamma dG(\gamma)}{G(\hat{\gamma}_g)} \geq \frac{f}{1-\pi}. \quad (9)$$

The green equilibrium exists if $\hat{\gamma}_g$ is sufficiently high (such that the left-hand side of (9) is high). By definition of $\hat{\gamma}_g$, given in (8), this is the case if Δ is sufficiently large. As the financial advantage of d-firms increases, these firms are able to attract more high-γ investors. As a result, d-firms' managers become more willing to adopt the green technology. We formalize this result in Proposition 1 below.

To complete the description of the green equilibrium, we compute output Y_g, pollu-

[16] Since all firms issue one unit of shares, the share prices are $p_{d,b} = G(\hat{\gamma}_b)$ and $p_{c,b} = 1 - G(\hat{\gamma}_b)$.

tion P_g, and investors' welfare W_g in this equilibrium.

$$Y_g = \alpha_c \left(1 - G\left(\hat{\gamma}_g\right)\right) + \left(\alpha_d - f\right) G\left(\hat{\gamma}_g\right), \; P_g = \pi G\left(\hat{\gamma}_g\right), \text{ and} \tag{10}$$

$$W_g = Y_g - \pi \int_0^{\hat{\gamma}_g} \gamma dG(\gamma) - \varepsilon \xi\left(P_g\right). \tag{11}$$

Conditions for brown and green equilibria Proposition 1 summarizes conditions for the existence of the two equilibria.

Proposition 1. *If $f > (1-\pi)\int_0^{\bar{\gamma}} \gamma dG(\gamma)$, only the brown equilibrium exists. If $f \leq (1-\pi)\int_0^{\bar{\gamma}} \gamma dG(\gamma)$, there exist $\bar{\gamma} \geq \bar{\Delta} > \underline{\Delta} > \frac{f}{1-\pi}$ such that*

(i) if $\Delta < \underline{\Delta}$, only the brown equilibrium exists;

(ii) if $\Delta \geq \bar{\Delta}$, only the green equilibrium exists;

(iii) if $\Delta \in \left[\underline{\Delta}, \bar{\Delta}\right)$, the green and brown equilibria coexist.

Furthermore, if the green and brown equilibria coexist, d-firms receive more funding in the green equilibrium, i.e., $\hat{\gamma}_g > \hat{\gamma}_b$, where $\hat{\gamma}_b$ and $\hat{\gamma}_g$ are given by (5) and (8), respectively.

Proof. See Appendix A.2. □

Proposition 1 delivers several results. First, if investors' green preferences are weak on average, i.e., $\int_0^{\bar{\gamma}} \gamma dG(\gamma) < \frac{f}{1-\pi}$, only the brown equilibrium exists. This is intuitive. From Lemma 1, shares of d-firms are held by low-γ investors. Therefore, if the adoption cost f is so large that even an average investor in the entire population prefers not to adopt the green technology, then only the brown equilibrium is possible.

If the adoption cost f is not that large, both equilibria are possible. Whether the brown or green equilibrium exists depends on the productivity difference Δ. In particular, the brown equilibrium exists if the difference is not too large, $\Delta < \bar{\Delta}$, and the green equilibrium exists if the difference is not too small, $\Delta \geq \underline{\Delta}$.

Proposition 1 also shows that the two equilibria can coexist, i.e., $\underline{\Delta} < \bar{\Delta}$. In this parameter region, the shareholder base of d-firms is larger in the green equilibrium, i.e., $\hat{\gamma}_g > \hat{\gamma}_b$. This is because in the green equilibrium, d-firms adopt the green technology and are able to attract investors with stronger green preferences $\gamma \in [\hat{\gamma}_b, \hat{\gamma}_g)$.

Figure 1 illustrates investor sorting when the two equilibria coexist. Panel (A) plots the payoffs from investing in c-firms, v_c (blue solid line), and in d-firms as functions of the green-preference parameter γ, as given by (1). For d-firms, we plot $v_d^g(\gamma)$ (red dashed line) and $v_d^b(\gamma)$ (red line with cross marks), which correspond to the cases in which d-firms adopt and do not adopt the green technology, respectively. If d-firms do not adopt, the marginal investor is $\hat{\gamma}_b$, whereas it is $\hat{\gamma}_g$ if they adopt.

For the two equilibria to coexist, the implied shareholder bases of d-firms must be consistent with investors' expectations. Specifically, the average d-firm's shareholder must be willing to adopt in the green equilibrium, $\psi(\hat{\gamma}_g) \geq \frac{f}{1-\pi}$, and unwilling to adopt in the brown equilibrium, $\psi(\hat{\gamma}_b) < \frac{f}{1-\pi}$, where $\psi(\hat{\gamma})$ is given in (3). Panel (B) plots the average preference of d-firm shareholders, $\psi(\hat{\gamma})$, as a function of the green preference strength of a marginal investor $\hat{\gamma}$, and confirms that this holds in this example: $\psi(\hat{\gamma}_g) > \frac{f}{1-\pi} > \psi(\hat{\gamma}_b)$.

Naturally, coexistence requires $\hat{\gamma}_g > \hat{\gamma}_b$. That is, investors with moderate green preferences, $\gamma \in [\hat{\gamma}_b, \hat{\gamma}_g)$, invest in d-firms only in the green equilibrium (Panel A), expecting those firms to adopt. By bringing additional capital to d-firms, they make the shareholder base sufficiently pro-green for adoption to occur.

To focus on the economically interesting case and reduce the number of scenarios to consider, we assume that the green equilibrium exists.

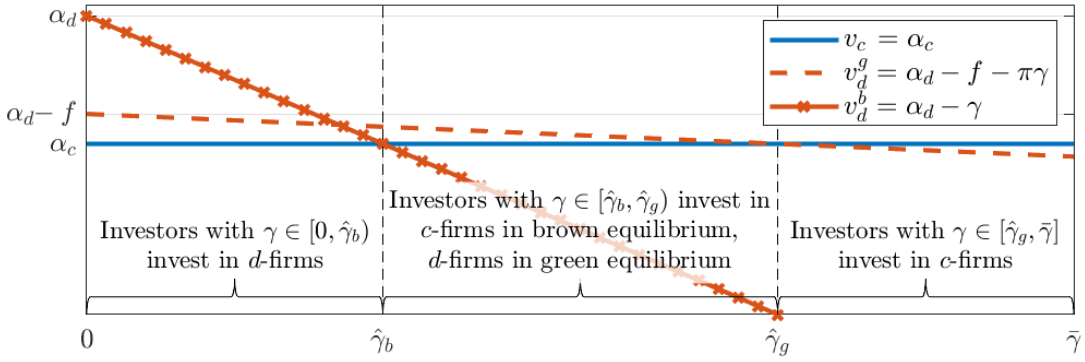
Assumption 1. *The green equilibrium exists, i.e.,* $f < (1-\pi)\int_0^{\bar{\gamma}} \gamma dG(\gamma)$ *and* $\Delta \geq \underline{\Delta}$.

3.2 Brown and green equilibria: Comparison

Proposition 1 implies that, if the two equilibria coexist, d-firms receive more funding in the green equilibrium. Therefore, although d-firms pollute less intensively in the green equilibrium, they are also larger, and so the aggregate pollution can in fact be higher than in the brown equilibrium. While this can be viewed as an interesting unintended consequence of sustainable finance, this is not the focus of our paper, so we assume that the green equilibrium features lower pollution.[17] This assumption holds if, for example,

[17] Such an unintended consequence can be viewed as a version of the Jevons paradox (Jevons, 1866). In the original paradox, improvements in the efficiency of coal use lead to increased consumption of coal.

(A) Expected utility as a function of the nonpecuniary parameter γ



(B) Average green preference of d-firms' shareholders, $\psi(\hat{\gamma})$

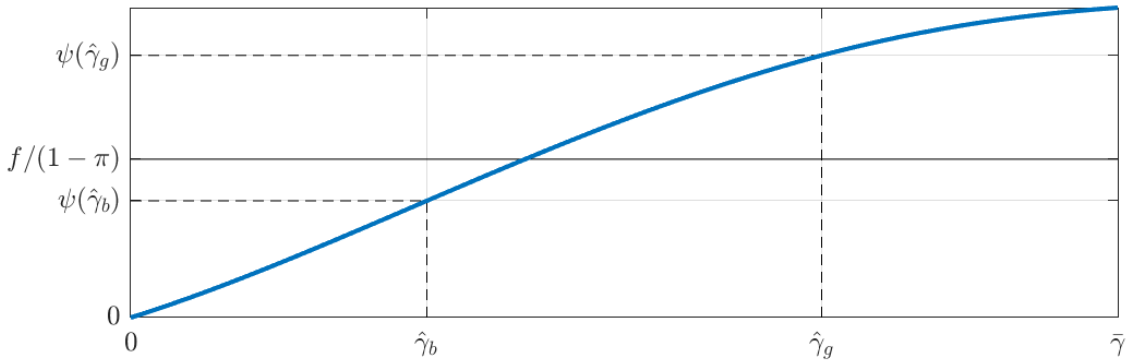


Figure 1: Panel (A): Values of investing one dollar in shares of c-firms (blue solid line, v_c), d-firms in green (red dashed line, v_d^g) and brown (red line with cross markers, v_d^b) equilibria as functions of the green preferences strength γ. Panel (B): Average green preference of d-firms' shareholders, $\psi(\hat{\gamma}) = (G(\hat{\gamma}))^{-1} \int_0^{\hat{\gamma}} \gamma dG(\gamma)$ as a function of the marginal investor preference $\hat{\gamma}$ (blue solid line). We also mark marginal investors, $\hat{\gamma}_b$ and $\hat{\gamma}_g$; average green preferences of d-firms' shareholders, $\psi(\hat{\gamma}_b)$ and $\psi(\hat{\gamma}_g)$, in the brown and green equilibria, respectively. Since $\psi(\hat{\gamma}_b) < \frac{f}{1-\pi} < \psi(\hat{\gamma}_g)$, the two equilibria coexist.

$G(\cdot)$ is weakly concave or π is sufficiently small.

Assumption 2. *Pollution in the green equilibrium is lower than in the brown equilibrium.*

Even if pollution is lower in the green equilibrium, adopting the green technology might be socially undesirable if the adoption cost is too high. Lemma 7 in Online Appendix C.2 proves an intuitive result that the green equilibrium is socially preferable if the adoption cost is sufficiently low.

Finally, the presence of multiple equilibria raises a natural question about equilibrium selection. We make a conservative assumption to ensure that our results are driven by fundamental economic forces rather than by coordination failures.

In our paper, adoption, despite being financially costly, attracts more green capital, as it reduces the pollution intensity of d-firms. As a result, d-firms pollute less intensively but also become bigger.

Assumption 3. *If the two equilibria coexist, the socially preferable one is played.*

3.3 Discussion

Even though investors are atomistic and do not internalize their impact on aggregate pollution, in equilibrium their investment choices still alleviate the pollution externality. As we discuss at the end of Section 2, in the no-green-preference benchmark, only the more financially attractive d-firms receive funding, and these firms never adopt the green technology. As a result, aggregate pollution and output are both higher in that world compared to either the brown or the green equilibria. This can be seen by comparing (4) with (7) and (10).[18]

Importantly, in the absence of the pollution externality, i.e., if $\varepsilon = 0$, investors' capital allocation and firms' adoption decisions are efficient. We show this in Corollary 1 in Section 4.1, which formally states the planner's problem. If such an externality is present, i.e., $\varepsilon > 0$, atomistic investors cannot fully resolve the externality issue, even though they dislike holding polluting shares. Consequently, pollution is too high in the laissez-faire economy, and there is room for policy interventions.

4 Policy analysis

We consider the efficient benchmark in Section 4.1. In Section 4.2, we show that the efficient allocation can be implemented via a mix of the green technology adoption subsidy and the pollution tax. Since the adoption investments are frequently not verifiable, we consider a model in which the policymaker has access only to a more readily available pollution tax in Section 4.3. We show there that the pollution tax alone is generally not sufficient to implement the efficient allocation.

[18] The presence of investors with green preferences always leads to a reduction in pollution relative to the no-green-preference benchmark. However, strengthening investors' green preferences is not necessarily associated with lower pollution. Lemma 8 in Online Appendix C.3 provides sufficient conditions under which strengthening the green preferences of *all* investors is associated with an increase in pollution.

4.1 Efficient allocation

We consider a utilitarian central planner who can choose the amounts of capital invested in d- and c-firms, as well as whether d-firms adopt the green technology.[19] Importantly, the planner does not face the constraint that the adoption decisions need to consider the preferences of d-firms' shareholders. The planner's objective is

$$\max_{\hat{\gamma},\mathtt{a}_d\in\{0,1\}} \underbrace{\left(\alpha_d - f\mathbb{1}_{\{\mathtt{a}_d=1\}}\right)G\left(\hat{\gamma}\right)+\alpha_c\left(1-G\left(\hat{\gamma}\right)\right)}_{\text{Output net of adoption costs}} - \underbrace{\left(\pi+(1-\pi)\,\mathbb{1}_{\{\mathtt{a}_d=0\}}\right)\int_0^{\hat{\gamma}}\gamma dG\left(\gamma\right)}_{\text{Nonpecuniary disutility}} - \underbrace{\varepsilon\xi\left(\left(\pi+(1-\pi)\,\mathbb{1}_{\{\mathtt{a}_d=0\}}\right)G\left(\hat{\gamma}\right)\right)}_{\text{Pollution externality}}. \tag{12}$$

The planner invests $G\left(\hat{\gamma}\right)$ in d-firms and $1-G\left(\hat{\gamma}\right)$ in c-firms. It also chooses whether to incur the adoption cost to reduce pollution intensity of d-firms. These decisions determine the aggregate output (first term in (12)). The planner allocates shares of d-firms to low-γ investors as they suffer low disutility from holding polluting shares (second term in the same expression). Finally, the planner internalizes the impact of those decisions on the social harm of the aggregate pollution, as captured by the last term in (12). Proposition 2 characterizes the solution to the planner's problem.

Proposition 2. *There exists a threshold $\bar{f}^{CP}>0$ (defined in the proof) such that*

(i) if $f\leq\bar{f}^{CP}$, the planner invests $G\left(\hat{\gamma}_g^{CP}\right)$ in d-firms and $1-G\left(\hat{\gamma}_g^{CP}\right)$ in c-firms; d-firms adopt the green technology and are held by investors with $\gamma<\hat{\gamma}_g^{CP}$;

(ii) if $f>\bar{f}^{CP}$, the planner invests $G\left(\hat{\gamma}_b^{CP}\right)$ in d-firms and $1-G\left(\hat{\gamma}_b^{CP}\right)$ in c-firms; d-firms do not adopt the green technology and are held by investors with $\gamma<\hat{\gamma}_b^{CP}$.

The thresholds $\hat{\gamma}_g^{CP}$ and $\hat{\gamma}_b^{CP}$ are uniquely pinned down by

$$\hat{\gamma}_g^{CP}=\frac{\Delta-f}{\pi}-\varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right) \quad \textit{and} \quad \hat{\gamma}_b^{CP}=\Delta-\varepsilon\xi'\left(G\left(\hat{\gamma}_b^{CP}\right)\right). \tag{13}$$

Proof. See Appendix A.3. □

[19] As in the laissez-faire economy, we consider symmetric allocations such that all ex-ante identical firms make identical decisions. We think of that as a natural benchmark, as asymmetric equilibria are unlikely to be played in the laissez-faire economy.

Proposition 2 states that if the adoption cost is sufficiently small, $f \leq \bar{f}^{CP}$, the planner prefers to implement the green efficient allocation, in which d-firms adopt the green technology. In this case, the planner allocates capital of investors with $\gamma < \hat{\gamma}_g^{CP}$ to d-firms, such that the total amount of capital invested in d-firms is $G\left(\hat{\gamma}_g^{CP}\right)$.[20] As discussed above, the planner follows the threshold rule and allocates shares of d-firms to low-γ investors who suffer low disutility from holding polluting shares.

There are two differences between the green efficient allocation and the green laissez-faire equilibrium. First, the planner prefers d-firms to be smaller than in the laissez-faire green equilibrium. From (8) and (13), we see that $\hat{\gamma}_g^{CP} < \hat{\gamma}_g$, which implies that $K_d^{g,CP} = G\left(\hat{\gamma}_g^{CP}\right) < K_d^g = G\left(\hat{\gamma}_g\right)$. Unlike individual investors, the planner internalizes that investing in d-firms increases aggregate pollution, which in turn harms all investors.

Second, the planner does not need to respect the adoption rule (3) used by firms in the laissez-faire economy. Consequently, an average d-firm's shareholder might not be willing to adopt the green technology under the planner's allocation. That is, (3) might be violated if $\hat{\gamma} = \hat{\gamma}_g^{CP}$, even if it holds in the laissez-faire economy when $\hat{\gamma} = \hat{\gamma}_g > \hat{\gamma}_g^{CP}$.[21]

It is important to note that the difference between the efficient allocation and the laissez-faire economy only exists in the presence of the pollution externality, i.e., if $\varepsilon > 0$. If $\varepsilon = 0$, the efficient allocation is achieved in the laissez-faire economy. In particular, firm sizes chosen by the planner are the same as in the laissez-faire economy: from (13), $\hat{\gamma}_g^{CP} = \hat{\gamma}_g$ and $\hat{\gamma}_b^{CP} = \hat{\gamma}_b$ if $\varepsilon = 0$. Furthermore, if $f \leq \bar{f}^{CP}$—such that the planner prefers d-firms to adopt the green technology—the green laissez-faire equilibrium exists. Under Assumption 3, the green equilibrium is then played. If $f > \bar{f}^{CP}$, the brown laissez-faire equilibrium exists and is played under the same assumption.

Corollary 1. *In the absence of the pollution externality ($\varepsilon = 0$), the efficient allocation*

[20] In what follows, we focus on this case and do not discuss in detail the case in which non-adoption is socially preferable.

[21] The key reason why the planner prefers adoption when firms do not is that the planner compares welfare across equilibria, while firm managers do not internalize that non-adoption can lead to an equilibrium switch associated with a non-infinitesimal change in firm size and shareholder composition. We discuss this in more detail (and emphasize the importance of the adoption cost structure for this result) in Online Appendix C.6.

is achieved in the laissez-faire economy.

Proof. See Appendix A.4. □

Proposition 2 and Corollary 1 clearly show that the source of inefficiency in our economy is the pollution externality. In its presence, polluting d-firms are inefficiently large. Regulatory policies aimed at achieving the efficient allocation should reduce the size of d-firms, while also accounting for the fact that green technology adoption decisions are made by d-firms' shareholders. In particular, if the regulator seeks to implement the green efficient allocation, it must ensure that the average d-firm's shareholder is sufficiently pro-green and prefers adoption. The following section discusses regulatory tools that can be used to implement such an allocation.

4.2 Implementing the efficient allocation

Implementing the green efficient allocation requires reducing d-firms' size while keeping their shareholders willing to adopt the green technology. Naturally, two policy tools are sufficient to reach this goal. In this section, we show how this can be done via the pollution tax and the green technology adoption subsidy. In Section 5.2, we discuss other policy tools that can be used to achieve the same goal.

Suppose that at the beginning of $t = 1$, before investors make their portfolio choices, the regulator commits to imposing a pollution tax τ and a green technology adoption subsidy ς^f at $t = 2$. This policy implies that d-firms have to pay τ per unit of pollution, but their green technology adoption cost will be reduced to $f - \varsigma^f$. Tax proceeds net of subsidy expenses are rebated to investors in a lump-sum fashion.

The equilibrium characterization features two differences relative to the baseline model considered in Section 3.1. First, the value of investing a dollar in a d-firm becomes

$$v_d\left(\gamma, \mathsf{a}_d, \tau, \varsigma^f\right) = \alpha_d - \left(f - \varsigma^f\right) \mathbb{1}_{\{\mathsf{a}_d=1\}} - (\gamma + \tau)\left(\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}\right).$$

The value of investing a dollar in a c-firm remains $v_c = \alpha_c$. Therefore, the green preference

of a marginal investor who is indifferent between investing in c- and d-firms is

$$\hat{\gamma}_b(\tau) = \Delta - \tau \quad \text{and} \quad \hat{\gamma}_g\left(\tau, \varsigma^f\right) = \frac{\Delta - \left(f - \varsigma^f\right)}{\pi} - \tau. \tag{14}$$

Naturally, (14) simplifies to (5) and (8) if $\tau = \varsigma^f = 0$. Since d-firms pollute in any equilibrium, a higher tax means that they become less financially attractive, and so only low-γ investors are willing to invest in them, i.e., $\frac{d\hat{\gamma}_b}{d\tau} = \frac{d\hat{\gamma}_g}{d\tau} = -1$. A higher adoption subsidy, in contrast, makes d-firms more financially attractive and thus increases their size, but only in the green equilibrium in which d-firms actually adopt, i.e., $\frac{d\hat{\gamma}_g}{d\varsigma^f} > \frac{d\hat{\gamma}_b}{d\varsigma^f} = 0$.

The second difference due to the policies is that managers of d-firms take into account that their firms will be taxed heavily unless they adopt the green technology, and that adoption is cheaper in the presence of the subsidy. The green equilibrium requires

$$\frac{\int_0^{\hat{\gamma}_g(\tau,\varsigma^f)} \gamma dG(\gamma)}{G\left(\hat{\gamma}_g(\tau,\varsigma^f)\right)} + \tau \geq \frac{f - \varsigma^f}{1 - \pi}, \tag{15}$$

where $\hat{\gamma}_g(\tau, \varsigma^f)$ is given in (14). An increase in ς^f makes (15) more likely to be satisfied. Indeed, a higher ς^f reduces the effective adoption cost (the right-hand side goes down) and increases the green preference of a marginal shareholder $\hat{\gamma}_g(\tau, \varsigma^f)$ (the left-hand side goes up). The effect of a higher τ is more subtle. On the one hand, a higher τ makes it more expensive for d-firms to operate a highly polluting brown technology, which makes (15) more likely to be satisfied (the left-hand side goes up). On the other hand, a higher tax makes d-firms' shareholders on average less concerned about the greenness of their portfolios, which means that managers of d-firms are less willing to pay the adoption cost (the left-hand side goes down). We discuss these two effects in more detail in Section 4.3.

Overall, the pollution tax and the adoption subsidy both affect d-firms' size and adoption decisions. The regulator can implement the green efficient allocation using a combination of these tools.

Lemma 2. *A sufficiently high adoption subsidy $\varsigma^f \geq \bar{\varsigma}^f \geq 0$ ($\bar{\varsigma}^f$ is defined in the proof) and pollution tax $\tau = \frac{\varsigma^f}{\pi} + \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$, where $\hat{\gamma}_g^{CP}$ is given by (13), implement the green efficient allocation.*

Proof. See Appendix A.5. □

An interesting implication of Lemma 2 is that the pollution tax needed to restore the green efficient allocation is generally higher than the marginal externality, i.e., it deviates from the Pigouvian benchmark, $\tau > \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$. Intuitively, a sufficiently high adoption subsidy can always incentivize d-firms to adopt the green technology. However, as follows from the second equation in (14), a higher subsidy does not correct the size of d-firms but instead makes adopting d-firms larger. To compensate for this, the pollution tax needs to be higher than the Pigouvian benchmark.

In the model, the adoption subsidy is a natural tool to incentivize d-firms to adopt the green technology. However, in reality, it is not easily available to policymakers because adoption is frequently not verifiable. In the following section, we therefore consider a regulator who has access only to a more readily available pollution tax.[22] While it punishes heavy polluters and thus also incentivizes d-firms to adopt, the pollution tax is generally not sufficient to achieve the green efficient allocation. In Section 5.2, we discuss how other policy tools in combination with the pollution tax can be used to achieve the green efficient allocation.

4.3 Pollution tax

4.3.1 Impact of the tax on the economy

Consider the same setup as in Section 4.2 but with zero adoption subsidy, $\varsigma^f = 0$. As discussed in that section, a higher pollution tax reduces the size of d-firms in any equilibrium. Consequently, in a given equilibrium, an appropriate tax can always reduce the size of d-firms to the efficient level. That is, if adoption decisions are exogenous—meaning that d-firms adopt/do not adopt the green technology in the green/brown equilibrium irrespective of their firms' shareholder bases—the pollution tax is sufficient to implement the efficient allocation.

[22] Carbon taxes are widely used by regulators. According to the World Bank's report (World Bank, 2025), there are 80 carbon pricing instruments implemented worldwide as of 2025, covering around 28% of global greenhouse gas emissions.

Lemma 3. *There exist unique* $\tau_g^* = \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right) > 0$ *and* $\tau_b^* = \varepsilon\xi'\left(G\left(\hat{\gamma}_b^{CP}\right)\right) > 0$, *where* $\hat{\gamma}_g^{CP}$ *and* $\hat{\gamma}_b^{CP}$ *are given by* (13), *that maximize investors' welfare in the green and brown equilibria, respectively. At these tax levels, firm sizes are the same as in the efficient allocation, i.e.,* $\hat{\gamma}_g\left(\tau_g^*\right) = \hat{\gamma}_g^{CP}$ *and* $\hat{\gamma}_b\left(\tau_b^*\right) = \hat{\gamma}_b^{CP}$. *Furthermore,* $\tau_g^*(\varepsilon)$ *and* $\tau_b^*(\varepsilon)$ *increase in the externality strength* ε.

Proof. See Appendix A.6. □

Crucially though, the pollution tax does affect adoption incentives, and setting $\tau = \tau_g^*$ can make the green equilibrium non-existent. Evaluating (15) at $\varsigma^f = 0$, we see that the green technology is adopted if and only if

$$\psi^\tau\left(\hat{\gamma}, \tau\right) \equiv \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G\left(\hat{\gamma}\right)} + \tau \geq \frac{f}{1-\pi}. \tag{16}$$

The effect of τ on the willingness to adopt $\psi^\tau\left(\hat{\gamma}, \tau\right)$ can be decomposed into two channels,

$$\frac{d\psi^\tau}{d\tau} = \underbrace{\frac{\partial\psi^\tau}{\partial\tau}}_{\text{Direct effect}} + \underbrace{\frac{d\hat{\gamma}}{d\tau}\frac{\partial\psi^\tau}{\partial\hat{\gamma}}}_{\text{Shareholder-base effect}} = 1 - \frac{g\left(\hat{\gamma}\right)}{G\left(\hat{\gamma}\right)}\left(\hat{\gamma} - \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G\left(\hat{\gamma}\right)}\right). \tag{17}$$

Holding shareholder composition fixed, an increase in τ makes it more expensive for d-firms to operate a more polluting brown technology. As a result, they are willing to adopt the green technology under a higher adoption cost: $\frac{\partial\psi^\tau}{\partial\tau} > 0$. At the same time, an increase in τ incentivizes the most pro-green d-firms' shareholders to leave, reducing d-firms' incentives to incur the adoption cost. Therefore, the shareholder-base effect is negative, $\frac{d\hat{\gamma}}{d\tau}\frac{\partial\psi^\tau}{\partial\hat{\gamma}} < 0$. If the shareholder-base effect dominates the direct effect, an increase in τ makes d-firms less willing to adopt the green technology, and the green equilibrium might cease to exist. It is therefore important to understand when the shareholder-base effect is strong.

From (17), the strength of the shareholder-base effect is determined by

$$\frac{\partial\psi^\tau}{\partial\hat{\gamma}} = \frac{g\left(\hat{\gamma}\right)}{G\left(\hat{\gamma}\right)}\left(\hat{\gamma} - \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G\left(\hat{\gamma}\right)}\right). \tag{18}$$

This equation makes clear that the shareholder-base effect is strong under two conditions:

1) there is substantial investor mass near $\hat{\gamma}$ relative to the total mass of d-firms' shareholders, i.e., $g(\hat{\gamma})/G(\hat{\gamma})$ is large; and 2) d-firms' shareholders are sufficiently polarized such that there is a large gap between the marginal and average investors' preferences, i.e., $\hat{\gamma} - \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G(\hat{\gamma})}$ is large. Under the first condition, a small change in $\hat{\gamma}$ leads to a large mass of investors reallocating their capital to c-firms; under the second, the induced composition change substantially alters the average green preference of d-firms' shareholders.

To clearly illustrate forces at work, we consider an example in which we make specific assumptions on the shape of the investor preference distribution.

Example 1. The distribution of investor preferences is a mixture of two power distributions,

$$G(\gamma) = w\left(\frac{\gamma}{\bar{\gamma}}\right)^a + (1-w)\left(1 - \left(1 - \frac{\gamma}{\bar{\gamma}}\right)^a\right), \tag{19}$$

where $w \in [0,1]$ and $a > 1$. The corresponding density function, with $w = 1/2$, is shown in panel (A) of Figure 2. There are two investor groups. A fraction w consists of investors whose preferences are relatively more concentrated toward $\gamma = \bar{\gamma}$, and a fraction $1-w$ consists of investors whose preferences are relatively more concentrated toward $\gamma = 0$. The parameter a captures how polarized preferences of the two investor groups are. If a is large, investor preferences are strongly polarized: preferences of all investors from the first (second) group are close to $\bar{\gamma}$ (0). In contrast, if a is close to one, investor preferences in both groups are close to uniform. By varying w and a we can, therefore, control the relative weights of the two groups and preference polarization across them. In Section 5.1, we come back to this example and explore how w and a affect the strength of the shareholder-base effect.

In this example, a marginal investor $\hat{\gamma}_g(0)$ is strongly concerned about greenness in the absence of the tax. Shareholders of d-firms then support the adoption (in panel (D), $\psi^\tau(\hat{\gamma}_g(0), 0) > \frac{f}{1-\pi}$). Importantly, the initial shareholder base of d-firms is highly polarized, with investors of both major groups having a comparable presence in it.

An increase in the pollution tax makes a marginal investor less concerned about

pollution, i.e., $\hat{\gamma}_g(\tau)$ declines (panel (B) in the same figure). Such a change has a strong impact on the average preference of the shareholder base (panel C): a small reduction in $\hat{\gamma}_g$ induces a large mass of high-γ investors to become shareholders of c-firms. As many high-γ investors leave d-firms, they end up mostly held by investors with substantially weaker green preferences. The shareholder-base effect here is particularly strong and dominates the direct effect, and so the willingness to adopt $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right)$ declines and crosses $\frac{f}{1-\pi}$ at $\tau = \underline{\tau}_1$ (panel D).

If the tax is sufficiently high, e.g., $\tau = \bar{\tau}_1$, almost all investors of the high-γ group switch to become shareholders of c-firms. In this case, d-firms' shareholder base is much less polarized as they are held almost entirely by low-γ investors. A marginal increase in τ has a small effect on the average preference of d-firms' shareholders. At this point, the shareholder-base effect is weak, and $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right)$ becomes an increasing function.

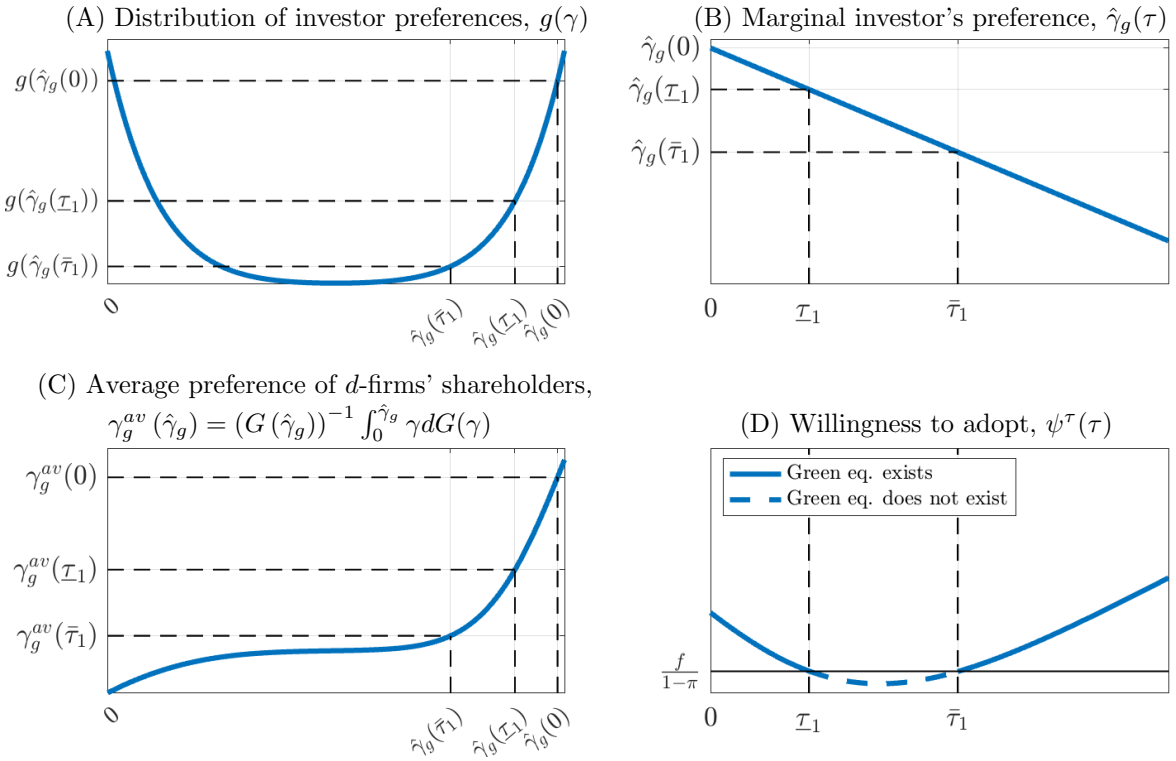


Figure 2: Panel (A): Probability density function of the distribution of investor preferences, $g(\gamma)$. Panel (B): Preference of a marginal investor as a function of pollution tax, $\hat{\gamma}_g(\tau)$. Panel (C): Average preference of d-firms' shareholders, $\gamma_g^{av}\left(\hat{\gamma}_g\right) = \left(G\left(\hat{\gamma}_g\right)\right)^{-1} \int_0^{\hat{\gamma}_g} \gamma dG(\gamma)$, as a function of the preference of a marginal investor $\hat{\gamma}_g$. Panel (D): Willingness to adopt the green technology, $\psi^{\tau}(\hat{\gamma}_g(\tau), \tau)$; green equilibrium exists if and only if $\psi^{\tau}(\hat{\gamma}_g(\tau), \tau) \geq \frac{f}{1-\pi}$. Appendix B provides numerical values used for these graphs.

Overall, if the tax is sufficiently low, $\tau < \underline{\tau}_1$, d-firms' shareholders are sufficiently

pro-green to adopt. If the tax is high, $\tau > \bar{\tau}_1$, the financial cost of operating the brown technology is so high that d-firms adopt even though their shareholder base consists of low-γ investors. If τ is in the intermediate range, $\tau \in (\underline{\tau}_1, \bar{\tau}_1)$, the financial cost of operating the brown technology is not too high but d-firms' shareholders are not sufficiently pro-green. As a result, d-firms' managers do not adopt the green technology.

Proposition 3 confirms that the results of Example 1 hold in a more general setting.

Proposition 3. *There exists* $\mathcal{S}_\tau^g = \bigcup_{i=1}^N (\underline{\tau}_i, \bar{\tau}_i)$, *where* $\frac{f}{1-\pi} > \bar{\tau}_N > \underline{\tau}_N > \cdots > \underline{\tau}_1 \geq 0$, *such that the green equilibrium does not exist if and only if* $\tau \in \mathcal{S}_\tau^g$; *moreover,* $\mathcal{S}_\tau^g$ *is nonempty if* Δ *is sufficiently close to* $\underline{\Delta}$, *and the shareholder-base effect dominates the direct effect of taxation,* $\frac{d\psi^\tau}{d\tau}\big|_{\tau=0} < 0$. *If the green equilibrium does not exist, the brown equilibrium exists. Furthermore, in any equilibrium, an increase in* τ *leads to reductions in the amount of capital raised by d-firms, aggregate output, and pollution.*

Proof. See Appendix A.7. □

Proposition 3 shows that the green equilibrium exists if the tax is sufficiently low or sufficiently high. However, if the shareholder-base effect is strong, the green equilibrium ceases to exist for the intermediate tax levels.[23] In addition, in any equilibrium, an increase in the tax makes d-firms relatively less financially attractive, and so they receive less funding and pollute less. The aggregate output (adjusted for tax proceeds rebated to investors) also declines as a result of capital reallocation to less productive c-firms.

4.3.2 Optimal tax

Lemma 3 shows that $\tau = \tau_g^*$ brings the size of d-firms in the green equilibrium to its green efficient level. However, at this tax, the shareholder base of d-firms may not be sufficiently pro-green for the green equilibrium to exist. In that case, the pollution tax alone is insufficient to implement the green efficient allocation.

[23] In Example 1, the green equilibrium does not exist if and only if $\tau \in (\underline{\tau}_1, \bar{\tau}_1)$. Proposition 3 shows that in general, the green equilibrium does not exist if and only if $\tau \in \mathcal{S}_\tau^g$, where $\mathcal{S}_\tau^g$ is a union of intervals. This set is nonempty if the shareholder-base effect is sufficiently strong.

Proposition 4. *There exists* $\mathcal{S}_\varepsilon^g = \bigcup_{i=1}^{N} (\underline{\varepsilon}_i, \bar{\varepsilon}_i)$*, where* $\bar{\varepsilon}_N > \underline{\varepsilon}_N > \cdots > \underline{\varepsilon}_1 \geq 0$*,* $\tau_g^* (\underline{\varepsilon}_i) = \underline{\tau}_i$ *and* $\tau_g^* (\bar{\varepsilon}_i) = \bar{\tau}_i$*, and where* $\underline{\tau}_i$ *and* $\bar{\tau}_i$ *are defined in Proposition 3, such that the optimal tax that sustains the green equilibrium* $\tau^*(\varepsilon)$ *is as follows:*

(i) if $\varepsilon \notin \mathcal{S}_\varepsilon^g$*,* $\tau^*(\varepsilon) = \tau_g^*(\varepsilon)$*, and the green efficient allocation is achieved;*

(ii) if $\varepsilon \in \mathcal{S}_\varepsilon^g$*,* $\tau^*(\varepsilon) \neq \tau_g^*(\varepsilon)$*, and the green efficient allocation is not achievable. Specifically, if* $\varepsilon \in (\underline{\varepsilon}_i, \bar{\varepsilon}_i)$*, then* $\tau^*(\varepsilon)$ *is either* $\underline{\tau}_i$ *or* $\bar{\tau}_i$*.*

Proof. See Appendix A.8. □

The regulator sets a positive tax to reduce the size of d-firms and, hence, the amount of pollution they produce. If the externality is weak, $\varepsilon \leq \underline{\varepsilon}_1$, only a small intervention is needed to fully correct the externality and thus implement the green efficient allocation. Such an intervention does not affect the shareholder base composition of d-firms too much, and d-firms adopt the green technology (that is, the green equilibrium exists). If the externality is strong, $\varepsilon \geq \bar{\varepsilon}_N$, the optimal tax is high, and so d-firms' managers adopt the green technology even if their shareholders are low-γ investors. The green equilibrium, therefore, also exists in this case.

If the externality is of intermediate strength, the tax that implements the green efficient allocation, $\tau_g^*(\varepsilon)$, makes the green equilibrium non-existent if the shareholder-base effect is sufficiently strong. The regulator then deviates from $\tau_g^*(\varepsilon)$. Panel (A) of Figure 3 illustrates this scenario using the assumptions of Example 1. Specifically, the green equilibrium does not exist if $\tau \in (\underline{\tau}_1, \bar{\tau}_1)$. In this figure, $\tau_g^*(\varepsilon)$ falls into this range, and the regulator sets $\tau^*(\varepsilon) = \underline{\tau}_1 < \tau_g^*(\varepsilon)$. Although this tax implies an under-correction of the externality—the derivative of the welfare function $W_g(\tau)$ is positive at $\underline{\tau}_1$—it keeps the d-firms' shareholder base sufficiently pro-green for the green technology adoption.

In panel (A) of Figure 3, the regulator optimally under-corrects the externality by setting $\tau^* (\varepsilon) = \underline{\tau}_1 < \tau_g^*(\varepsilon)$. As the externality strengthens, the regulator switches to over-correcting the externality and sets $\tau^* (\varepsilon) = \bar{\tau}_1 > \tau_g^*(\varepsilon)$. At this tax, d-firms are smaller and thus pollute less than at $\underline{\tau}_1$. As the pollution becomes a larger social concern, the

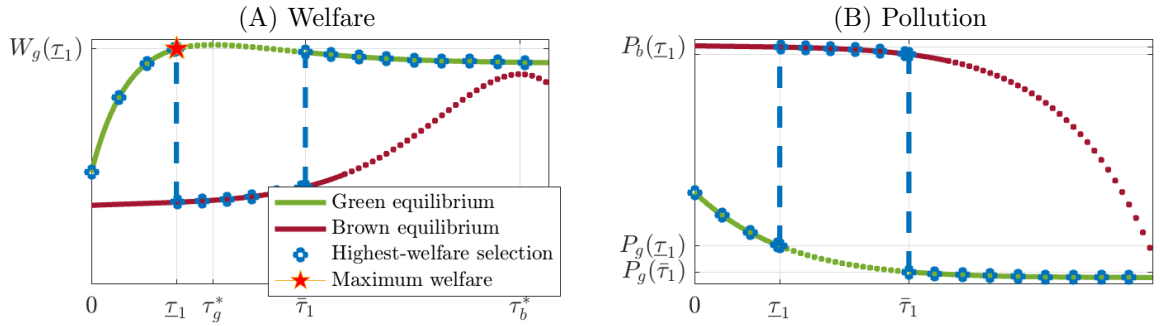


Figure 3: Welfare (panel A) and pollution (panel B) in the green equilibrium, the brown equilibrium and under the highest-welfare selection criterion as functions of pollution tax τ. For green and brown equilibria in both panels, solid/dotted lines show variables if a corresponding equilibrium exists/does not exist when adoption decisions are made based on shareholders' preferences. In panel (A), star marks welfare under the optimal tax. The externality strength is $\varepsilon \in (\underline{\varepsilon}_1, \bar{\varepsilon}_1)$. Appendix B provides numerical values used for these graphs.

regulator prefers over-correction of the externality to under-correction as that implies an overall lower pollution.

Figure 4 shows the optimal tax as a function of the externality strength. As follows from our discussion above, if the externality is sufficiently weak or strong, $\varepsilon < \underline{\varepsilon}_1$ or $\varepsilon > \bar{\varepsilon}_1$, the green efficient allocation is achievable by setting $\tau = \tau_g^*(\varepsilon)$. If the externality is of intermediate strength, the regulator first under-corrects it, i.e., $\tau^*(\varepsilon) = \underline{\tau}_1$ if $\varepsilon \in (\underline{\varepsilon}_1, \varepsilon_1^s]$, and then over-corrects it, i.e., $\tau^*(\varepsilon) = \bar{\tau}_1$ if $\varepsilon \in (\varepsilon_1^s, \bar{\varepsilon}_1)$. Corollary 2 formalizes this result.

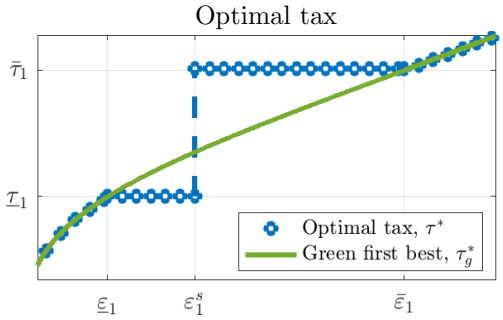


Figure 4: Optimal tax that sustains the green equilibrium as a function of the externality strength ε. Appendix B provides numerical values used for this graph.

Corollary 2. *The optimal tax $\tau^*(\varepsilon)$, defined in Proposition 4, (weakly) increases in the externality strength ε. Specifically, if $\varepsilon \in (\underline{\varepsilon}_i, \bar{\varepsilon}_i)$, then there exists $\varepsilon_i^s \in (\underline{\varepsilon}_i, \bar{\varepsilon}_i)$ such that $\tau^*(\varepsilon) = \underline{\tau}_i$ if $\varepsilon \in (\underline{\varepsilon}_i, \varepsilon_i^s]$ and $\tau^*(\varepsilon) = \bar{\tau}_i$ if $\varepsilon \in (\varepsilon_i^s, \bar{\varepsilon}_i)$.*

Proof. See Appendix A.8. □

Our analysis in this section shows that an increase in the tax can be counterproductive and may even lead to higher pollution (see panel (B) in Figure 3). The key mechanism is the shareholder-base effect: a higher tax can weaken support for green technology adoption among d-firms' shareholders. Given the central role of this effect, we examine it in more detail in the next section.

5 Additional analysis

Section 5.1 characterizes conditions under which the shareholder-base effect is strong and the pollution tax deviates from the Pigouvian benchmark. Section 5.2 analyzes subsidies to c-firms.

5.1 Investor composition and shareholder-base effect

The key force behind the nonattainability of the green efficient allocation under pollution taxation is the shareholder-base effect. When this effect is strong, such that (17) is negative, a higher tax weakens d-firms' shareholders' incentives to adopt the green technology. In Section 4.3, we show that the strength of this effect is governed by the shape of the investor preference distribution. Here, we further characterize this mechanism by focusing on a specific distribution considered in Example 1.

The distribution function (19) depends on two parameters. The weight w governs how *balanced* the investor base is between the two investor groups, and a governs how *polarized* the two groups are. The following lemma shows that the shareholder-base effect tends to be strong if the investor base is balanced and polarized.

Lemma 4. *Suppose that the investor preference distribution is given by (19). The shareholder-base effect is weak, in the sense that a higher pollution tax always increases the willingness of d-firms to adopt the green technology, if investor composition is*

(i) not too polarized: for a given $w \in (0,1)$, $a < \underline{a}$, where $\underline{a} > 1$;

(ii) imbalanced: for a given $a > 1$, $w < \underline{w}$ or $w > \bar{w}$, where $1 > \bar{w} \geq \underline{w} > 0$.

In contrast, if investor composition is balanced and polarized, $w \in (0,1)$ and $a > \bar{a}$, the

shareholder-base effect can be strong.[24]

Proof. See Appendix A.9. □

Recall from (18) that the shareholder-base effect is strong if there is a substantial investor mass near $\hat{\gamma}$, and the gap between the marginal and average investors' preferences is large. Part (i) of Lemma 4 shows that the shareholder-base effect is weak when the investor base is not too polarized, that is, when a is sufficiently small (the red dashed line in Figure 5). In this case, the investor distribution is fairly uniform, and the mass of investors near any γ is never too large. As a result, an increase in the tax and the resulting reallocation of near-$\hat{\gamma}$ investors to c-firms does not have a strong effect on the average preference of d-firms' shareholders.

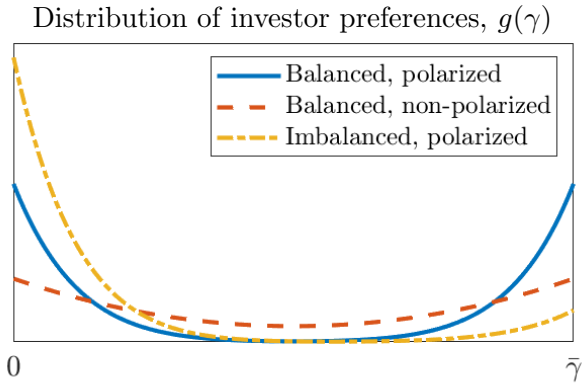


Figure 5: Probability density function of the distribution of investor preferences, $g(\gamma)$. The distribution, given by (19), is a mixture of two power distributions. Blue solid line ("Balanced, polarized"): $w = 0.5$, $a = 10$. Red dashed line ("Balanced, non-polarized"): $w = 0.5$, $a = 4$. Yellow dot-dashed line ("Imbalanced, polarized"): $w = 0.1$, $a = 10$. The shareholder-base effect is weak in the latter two cases.

Part (ii) further shows that the shareholder-base effect is weak when the investor base is imbalanced, with w close to 0 or 1 (the yellow dot-dashed line in Figure 5 shows the case with a small w). If w is close to 0 (1), the mass of high-γ investors in the population is small (large), so the average preference of d-firms' shareholders is always determined primarily by the low-γ (high-γ) group. The shareholder-base effect is then weak as the tax has a relatively weak effect on the average preference of d-firms' shareholders.

[24] Lemma 4 shows that for a given $w \in (0,1)$, the shareholder-base effect is weak if $a < \underline{a}$ but can be strong if $a > \bar{a}$. While we are not able to analytically show that $\underline{a} = \bar{a}$, we find via numerical simulations that this is indeed the case. That is, there exists a threshold $\hat{a} = \hat{a}(w)$ such that the shareholder-base effect is weak if and only if $a < \hat{a}$ (see Figure 9 in Online Appendix C.4).

If the shareholder-base effect is weak, the pollution tax both reduces the size of d-firms and strengthens their shareholders' incentives to adopt the green technology. As a result, the green efficient allocation can be implemented by a Pigouvian tax.

Corollary 3. *If the shareholder-base effect is weak, the tax $\tau_g^*(\varepsilon)$ always implements the green efficient allocation.*

Proof. If the shareholder-base effect is weak, the set $\mathcal{S}_\tau^g$, defined in Proposition 3, is empty. The corollary then follows directly from Propositions 3 and 4. □

5.2 Subsidy to c-firms

A common policy tool used by regulators worldwide is subsidies to clean firms (e.g., Taylor, 2020). Given their real-life importance, we analyze such subsidies in this section.

5.2.1 Setup

At the beginning of $t = 1$, the regulator imposes a subsidy $\varsigma \geq 0$, such that each c-firm receives a transfer ςk_c at $t = 2$, where k_c is the capital amount raised from investors. The subsidy is financed by lump-sum taxation of all investors. Effectively, the subsidy makes c-firms more financially attractive by reducing the productivity difference from Δ to $\Delta - \varsigma$. Unlike the pollution tax, the subsidy does not affect the adoption incentives: As in the baseline model, the green technology is adopted if and only if (3) holds.

An increase in the subsidy results in d-firms receiving less funding and polluting less in any equilibrium. Shareholder composition also changes as investors with moderate green preferences switch to c-firms. Consequently, even if the green equilibrium exists under the zero subsidy, it ceases to exist if the subsidy size is sufficiently large, $\varsigma > \bar{\varsigma}$. Proposition 6 in Online Appendix C.5 proves these intuitive results.

As with the pollution tax, an appropriate subsidy can always reduce the size of d-firms to the efficient level in a given equilibrium. The subsidy is therefore sufficient to implement the efficient allocation if adoption decisions are exogenous.

Lemma 5. *There exist unique increasing functions $0 < \varsigma_g^*(\varepsilon) < \varsigma_b^*(\varepsilon)$ that maximize investors' welfare in the green and brown equilibria, respectively.*

Proof. See Appendix A.10. □

When the adoption decisions are endogenous, the subsidy is not sufficient to implement the green efficient allocation when the externality is sufficiently strong.

Proposition 5. *There exist* $0 \leq \underline{\varepsilon}^{\varsigma} < \bar{\varepsilon}^{\varsigma}$ *such that, relative to the green efficient allocation, the optimal subsidy* $\varsigma^*(\varepsilon)$

(i) fully corrects the externality, $\varsigma^*(\varepsilon) = \varsigma_g^*(\varepsilon)$*, if* $\varepsilon \leq \underline{\varepsilon}^{\varsigma}$*;*

(ii) over-corrects the externality, $\varsigma^*(\varepsilon) = \varsigma_b^*(\varepsilon) > \varsigma_g^*(\varepsilon)$*, if* $\varepsilon > \bar{\varepsilon}^{\varsigma}$*;*

(iii) under-corrects the externality, $\varsigma^*(\varepsilon) = \bar{\varsigma} < \varsigma_g^*(\varepsilon)$*, if* $\varepsilon \in (\underline{\varepsilon}^{\varsigma}, \bar{\varepsilon}^{\varsigma}]$*.*

Proof. See Appendix A.11. □

The optimal subsidy achieves the green efficient allocation only if the externality is weak, $\varepsilon < \underline{\varepsilon}^{\varsigma}$ (panel (A) in Figure 6). If $\varepsilon = \underline{\varepsilon}^{\varsigma}$ and $\varsigma = \varsigma_g^*(\underline{\varepsilon}^{\varsigma}) = \bar{\varsigma}$, the shareholder base of d-firms shrinks to the point where their average shareholder is indifferent between adopting the green technology and not. A further increase in the subsidy size makes the green equilibrium non-existent. If $\varepsilon > \underline{\varepsilon}^{\varsigma}$, the highest welfare in the green equilibrium is therefore achieved at $\varsigma = \bar{\varsigma}$, where the externality is under-corrected. However, as long as ε is not too high, $\varepsilon < \bar{\varepsilon}^{\varsigma}$, this under-correction is small, and the regulator cannot achieve a higher welfare in the brown equilibrium even by setting $\varsigma = \varsigma_b^*(\varepsilon)$ (panel B).

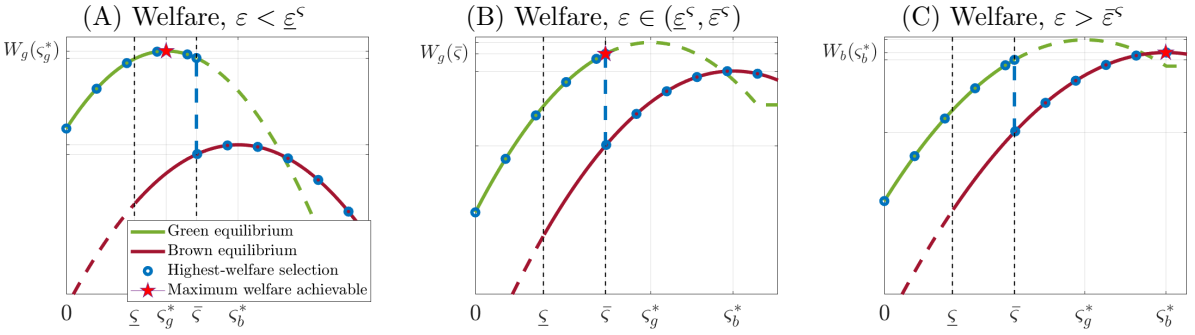


Figure 6: Welfare in the green equilibrium, the brown equilibrium and under the highest-welfare selection criterion as functions of the subsidy size ς. Panel (A): Weak externality, $\varepsilon < \underline{\varepsilon}^{\varsigma}$. Panel (B): Intermediate externality strength, $\varepsilon \in (\underline{\varepsilon}^{\varsigma}, \bar{\varepsilon}^{\varsigma})$. Panel (C): Strong externality, $\varepsilon > \bar{\varepsilon}^{\varsigma}$. For green and brown equilibria in all panels, solid/dashed lines show welfare if a corresponding equilibrium exists/does not exist when adoption decisions are based on shareholders' preferences. In all panels, star marks welfare under the optimal subsidy size. Appendix B provides numerical values used for these graphs.

If the externality is strong, $\varepsilon > \bar{\varepsilon}^{\varsigma}$, the regulator heavily subsidizes c-firms by setting $\varsigma = \varsigma_b^*(\varepsilon)$. Under this subsidy, the green equilibrium does not exist, and d-firms do not adopt the green technology. The overall pollution is low because these firms receive little capital. While costly financially, it is the only way for the regulator to substantially ameliorate the pollution externality. This case is illustrated in panel (C) in Figure 6.

Unlike the subsidy, the pollution tax incentivizes the green technology adoption by imposing a higher financial burden only on more polluting d-firms. The differences between the policies become evident if the externality is strong. In this case, the regulator wants to significantly reduce pollution by either heavily subsidizing c-firms or imposing a high tax on polluting d-firms. A large subsidy to c-firms keeps d-firms small but, at the same time, they never adopt the green technology. In contrast, if the tax is large, it is financially costly to pollute, and d-firms adopt the green technology even though their shareholders are not particularly pro-green. Therefore, unlike a high subsidy, a high tax can both keep d-firms small and incentivize their managers to adopt the green technology.

5.2.2 Implementing the efficient allocation

While neither the subsidy to c-firms nor the pollution tax alone is generally sufficient to implement the green efficient allocation, their combination can always achieve this outcome.

Lemma 6. *A sufficiently negative subsidy to c-firms $\varsigma \leq \hat{\varsigma} \leq 0$ ($\hat{\varsigma}$ is defined in the proof) and pollution tax $\tau = -\frac{\varsigma}{\pi} + \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$, where $\hat{\gamma}_g^{CP}$ is given by (13), implement the green efficient allocation.*

Proof. See Appendix A.12. □

A sufficiently high tax can always guarantee adoption but it does so at the cost of making d-firms inefficiently small. In this case, a *negative* subsidy to c-firms (equivalently, a positive subsidy to d-firms) is needed to enlarge d-firms to their efficient size. Simultaneously, the tax is adjusted to ensure adoption, implying that it exceeds the Pigouvian level.[25] This last result is reminiscent of Lemma 2, which shows that the optimal tax

[25]This implementation of the green efficient allocation is equivalent to a nonlinear pollution tax, where

exceeds the Pigouvian level if combined with the adoption subsidy.

6 Concluding remarks

Recent years have witnessed a substantial rise in sustainable investing, together with more active use of environmental regulation around the world. In this paper, we analyze the interaction between these two approaches, both aimed at tackling climate change. Our analysis yields several novel insights.

First, sustainable investing partially substitutes for regulation, but it also qualitatively changes how conventional environmental policy tools affect the aggregate economy. To highlight this difference, it is useful to compare the effects of a pollution tax in the baseline economy with those in the no-green-preference economy introduced at the end of Section 2. Figure 7 illustrates how output and pollution respond to a tax increase in the two economies.[26] Consider first the no-green-preference economy. When the tax is low, d-firms do not adopt the green technology and remain more financially attractive than c-firms, so all investment flows to them and pollution is therefore high. As the tax increases, d-firms switch to adopting, but, provided adoption costs are not too high, they continue to attract all investment, leading to lower but still positive pollution. Only when the tax becomes sufficiently high do c-firms become more financially attractive, at which point investment reallocates toward them and pollution falls to zero.

There are two key differences between this economy and the baseline economy in which investors have green preferences. First, for any given tax level, both output and pollution are always lower in the baseline model. This reflects a direct effect of investors' green preferences: Investors are willing to sacrifice financial returns to invest in less polluting firms. Second, in the no-green-preference economy, a higher tax is always associated with (weakly) lower output and pollution. In contrast, in the baseline economy, a higher

adopting d-firms' tax rate is $\tau^a = \tau + \frac{\varsigma}{\pi}$ per unit of pollution, and non-adopting d-firms' tax rate is $\tau^{na} = \tau + \varsigma$ per unit of pollution. By setting τ^{na} at a sufficiently high level, the regulator implements adoption; by varying τ^a, it reaches d-firms' optimal size. Relatedly, Hoffmann et al. (2017) find that the optimal carbon tax is nonlinear when firms face financial constraints.

[26] We focus on output and pollution rather than welfare because investors have different utility functions in the two economies.

tax can weaken d-firms' incentives to adopt the green technology, potentially leading to an increase in pollution (see also panel (B) of Figure 3). This novel shareholder-base effect arises because firms' shareholder compositions endogenously respond to regulation.

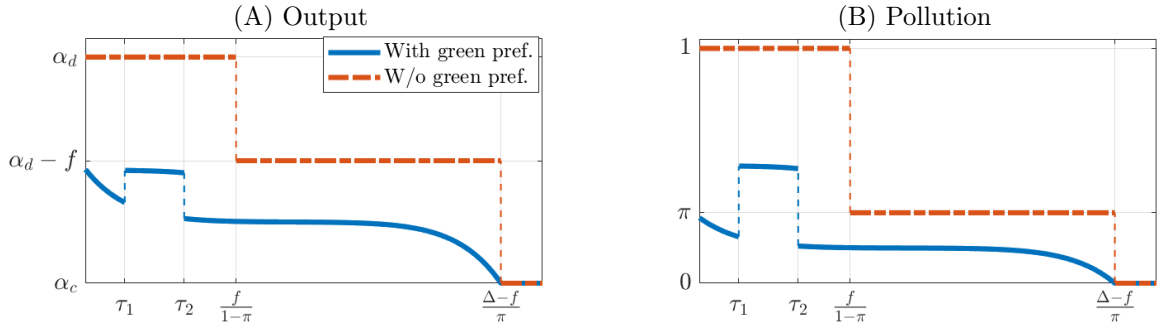


Figure 7: Output (panel A) and pollution (panel B) as functions of pollution tax τ in the baseline model in which investors have green preferences (solid blue lines) and in the no-green-preference economy (red dot-dashed lines). Appendix B provides numerical values used for these graphs.

Second, the shareholder-base effect is strong when investors' preferences are balanced and polarized. Our analysis in Section 5.1 shows that the shareholder-base effect is strongest when the investor base is both balanced and polarized, that is, when there is a comparable mass of investors with strong and weak green preferences. In contrast, when the investor base is more uniform, or dominated by a single investor group, the shareholder-base effect is always weak. In this case, the pollution tax operates in a qualitatively conventional way: It reduces the size of polluting firms and incentivizes them to adopt the green technology. As a result, aggregate pollution always declines with the tax. In contrast, if the shareholder-base effect is strong, a higher tax can lead to less adoption and higher pollution.

Third, the pollution tax alone is generally not sufficient to fully correct the externality. Corollary 2 shows that if the shareholder-base effect is strong, an increase in the pollution tax can reduce adoption incentives and raise pollution. This non-monotonicity has sharp policy implications. If the externality is relatively weak, the regulator optimally under-corrects the externality: a lower tax keeps polluting firms large but ensures their shareholders are sufficiently pro-green to sustain adoption. If, instead, pollution is a sufficiently large social concern, the regulator optimally over-corrects by setting the

tax high enough that d-firms adopt the green technology for purely financial reasons. In this environment, the use of an additional policy instrument can be welfare-improving. In particular, combining a sufficiently high pollution tax with a subsidy to d-firms can simultaneously discipline firm size and restore d-firms' incentives to adopt.

Going forward, our model can be extended in several directions. A particularly interesting avenue is to study the dynamic interaction between trading, green investment, and regulatory actions along the green transition, when the cost and efficacy of new technologies are highly uncertain. In Online Appendix C.7, we take a first step by modeling green adoption as a timing option: d-firms can either adopt early for all assets at a discounted average cost or wait and learn which assets are cheap to clean. The resulting forces are broadly in line with our baseline model. We show that the option to wait can weaken early-adoption incentives and eliminate the early-adoption equilibrium. Moreover, there is a two-way feedback between timing and shareholder composition: early commitment to adoption attracts more pro-green investors, which in turn sustains early adoption; in contrast, if investors expect d-firms to forgo early adoption, they anticipate that hard-to-clean assets will remain highly polluting, and so only investors with weak green preferences invest in d-firms. Finally, a pollution tax can delay option exercise through the shareholder-base effect and thereby increase pollution. A richer dynamic framework could explore these mechanisms in a multi-period setting and under regulatory uncertainty.

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Appendix

A Proofs

A.1 Lemma 1

Proof. Using (1), define $\hat{\gamma}$ as

$$v_c = v_d(\hat{\gamma}) \Leftrightarrow \alpha_c = \alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}} - \hat{\gamma}\left(\pi + (1-\pi)\mathbb{1}_{\{\mathsf{a}_d=0\}}\right) \Leftrightarrow \hat{\gamma} = \frac{\Delta - f\mathbb{1}_{\{\mathsf{a}_d=1\}}}{\pi + (1-\pi)\mathbb{1}_{\{\mathsf{a}_d=0\}}}.$$

If $\hat{\gamma} \in [0, \bar{\gamma}]$, investors with $\gamma = \hat{\gamma}$ are indifferent between investing in c- and d-firms. Since the cumulative distribution function of investor types $G(\cdot)$ is continuous, the mass of investors with $\gamma = \hat{\gamma}$ is zero. Investors with $\gamma < \hat{\gamma}$ (if any) strictly prefer to invest in d-firms. Investors with $\gamma > \hat{\gamma}$ (if any) strictly prefer to invest in c-firms. If $\hat{\gamma} < 0$, all investors strictly prefer to invest in c-firms. If $\hat{\gamma} > \bar{\gamma}$, all investors strictly prefer to invest in d-firms.

Given the shareholder composition, the amount of capital d-firms raise is $G(\hat{\gamma})$, and so $p_d = G(\hat{\gamma})$, so that an investor with $\gamma < \hat{\gamma}$ acquires $s_c^\gamma = 0$ units of c-firms' shares and $s_d^\gamma = 1/p_d = 1/G(\hat{\gamma})$ units of d-firms' shares. Analogously, $p_c = 1 - G(\hat{\gamma})$, and an investor with $\gamma > \hat{\gamma}$ acquires $s_c^\gamma = 1/(1 - G(\hat{\gamma}))$ units of c-firms' shares and $s_d^\gamma = 0$ units of d-firms' shares. □

A.2 Proposition 1

Proof. Recall from (3) that $\psi(\hat{\gamma}) = \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G(\hat{\gamma})}$. This function satisfies three properties: (1) $\psi(\hat{\gamma}) < \hat{\gamma}$; (2) $\lim_{\hat{\gamma}\to 0}\psi(\hat{\gamma}) = 0$ by L'Hospital's rule; (3) $\psi(\hat{\gamma})$ is an increasing function because

$$\frac{\partial \psi}{\partial \hat{\gamma}} = \frac{g(\hat{\gamma})}{G(\hat{\gamma})}\left(\hat{\gamma} - \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G(\hat{\gamma})}\right) > 0.$$

The green equilibrium exists if $\psi(\hat{\gamma}_g) \geq \frac{f}{1-\pi}$, where $\hat{\gamma}_g$ is given by (8). The brown equilibrium exists if $\psi(\hat{\gamma}_b) < \frac{f}{1-\pi}$, where $\hat{\gamma}_b$ is given by (5). The equilibrium characterization can be split into two cases.

Case 1: $f > (1-\pi)\int_0^{\bar{\gamma}} \gamma dG(\gamma)$. In this case, $\psi(\hat{\gamma}) \leq \int_0^{\bar{\gamma}} \gamma dG(\gamma) < \frac{f}{1-\pi}$ for any $\hat{\gamma} \in [0, \bar{\gamma}]$. Therefore, the green equilibrium does not exist, and the brown equilibrium does.

Case 2: $f \leq (1-\pi)\int_0^{\bar{\gamma}} \gamma dG(\gamma)$. Recall that $\psi(\hat{\gamma})$ is a continuous increasing function of $\hat{\gamma}$. Furthermore, $\lim_{\hat{\gamma}\to 0}\psi(\hat{\gamma}) = 0$ and $\psi(\bar{\gamma}) \geq \frac{f}{1-\pi}$. Therefore, there exists a unique $\underline{\Delta} > 0$ such that $\psi(\hat{\gamma}_g(\underline{\Delta})) = \frac{f}{1-\pi}$, where $\hat{\gamma}_g(\Delta)$ is given by (8). Similarly, there exists a unique $\bar{\Delta} \leq \bar{\gamma}$ such that $\psi\left(\hat{\gamma}_b\left(\bar{\Delta}\right)\right) = \frac{f}{1-\pi}$, where $\hat{\gamma}_b(\Delta)$ is given by (5). It follows that the green equilibrium exists if and only if $\Delta \geq \underline{\Delta}$, and the brown equilibrium exists if and only if $\Delta < \bar{\Delta}$.

Next, we prove that $\underline{\Delta} < \bar{\Delta}$. Suppose that $\Delta = \bar{\Delta}$ so that $\psi\left(\hat{\gamma}_b\left(\bar{\Delta}\right)\right) = \frac{f}{1-\pi}$, which implies $\hat{\gamma}_b\left(\bar{\Delta}\right) = \bar{\Delta} > \frac{f}{1-\pi}$, where we use the definition of $\hat{\gamma}_b$ (5) and the fact that $\psi(\hat{\gamma}) < \hat{\gamma}$. Since $\bar{\Delta} > \frac{f}{1-\pi}$, we have $\hat{\gamma}_g\left(\bar{\Delta}\right) = \frac{\bar{\Delta}-f}{\pi} > \bar{\Delta} = \hat{\gamma}_b\left(\bar{\Delta}\right)$. Because $\psi(\hat{\gamma})$ increases in $\hat{\gamma}$, we have $\psi\left(\hat{\gamma}_g\left(\bar{\Delta}\right)\right) > \psi\left(\hat{\gamma}_b\left(\bar{\Delta}\right)\right) = \frac{f}{1-\pi}$, which means that the green equilibrium exists if $\Delta = \bar{\Delta}$. Moreover, $\psi\left(\hat{\gamma}_g(\bar{\Delta})\right) > \frac{f}{1-\pi} = \psi(\hat{\gamma}_g(\underline{\Delta}))$, which implies that $\bar{\Delta} > \underline{\Delta}$ because $\psi(\hat{\gamma})$ increases in $\hat{\gamma}$ and $\hat{\gamma}_g(\Delta)$ increases in Δ.

Finally, we prove that $\hat{\gamma}_g > \hat{\gamma}_b$ if the green and brown equilibria coexist. Using (5) and (8), we can write $\hat{\gamma}_g - \hat{\gamma}_b = \frac{\Delta(1-\pi)-f}{\pi}$. Note that $\hat{\gamma}_g\left(\frac{f}{1-\pi}\right) = \frac{f}{1-\pi}$ and $\psi\left(\hat{\gamma}_g\left(\frac{f}{1-\pi}\right)\right) = \psi\left(\frac{f}{1-\pi}\right) < \frac{f}{1-\pi}$, which implies that the green equilibrium does not exist if $\Delta = \frac{f}{1-\pi}$. Recall that the green equilibrium exists if and only if $\Delta \geq \underline{\Delta}$. Therefore, $\underline{\Delta} > \frac{f}{1-\pi}$. Therefore, if the green equilibrium exists, then $\Delta \geq \underline{\Delta} > \frac{f}{1-\pi}$, and so $\hat{\gamma}_g - \hat{\gamma}_b = \frac{\Delta(1-\pi)-f}{\pi} > 0$. □

A.3 Proposition 2

Proof. The planner chooses the amount of capital invested in d-firms, K_d, and whether d-firms adopt the green technology. Since disutility from holding polluting shares increases with γ, the planner allocates shares of d-firms to low-γ investors, such that $K_d = G(\hat{\gamma})$.

Suppose that the planner chooses that d-firms do not adopt. Then it solves

$$W_b^{CP} = \max_{K_d \in [0,1]} \alpha_d K_d + \alpha_c (1 - K_d) - \int_0^{G^{-1}(K_d)} \gamma dG(\gamma) - \varepsilon \xi(K_d), \tag{20}$$

where the last term represents disutility of low-γ investors from holding polluting shares.

It is easy to see that the objective function is strictly concave, so we know that the first-order conditions are necessary and sufficient. Assuming an inner solution, $K_d \in (0,1)$, we get $\Delta - \varepsilon\xi'(K_d) - G^{-1}(K_d) = 0$. This equation clearly has a unique solution since the left-hand side is strictly monotone in K_d. Defining the threshold $\hat{\gamma}_b^{CP}$ as $K_d = G\left(\hat{\gamma}_b^{CP}\right)$, we can rewrite this equation as

$$\hat{\gamma}_b^{CP} = \Delta - \varepsilon\xi'\left(G\left(\hat{\gamma}_b^{CP}\right)\right).$$

If the planner chooses that d-firms adopt, then it solves

$$W_g^{CP} = \max_{K_d \in [0,1]} (\alpha_d - f)K_d + \alpha_c(1 - K_d) - \pi \int_0^{G^{-1}(K_d)} \gamma dG(\gamma) - \varepsilon\xi(\pi K_d). \quad (21)$$

Following the same steps as above, we can derive the equation for $\hat{\gamma}_g^{CP}$,

$$\hat{\gamma}_g^{CP} = \frac{\Delta - f}{\pi} - \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right).$$

Clearly, $\hat{\gamma}_g^{CP}$ and $\hat{\gamma}_b^{CP}$ are uniquely pinned down because $\xi(\cdot)$ is a convex function.

The planner chooses whether to adopt by comparing welfare in the two cases. Specifically, the planner chooses to adopt if and only if $W_g^{CP} - W_b^{CP} \geq 0$. Note that exists a unique $\bar{f}^{CP} > 0$ such that $W_g^{CP} - W_b^{CP} \geq 0$ if and only if $f \leq \bar{f}^{CP}$. To see that, note first that $W_g^{CP}(f)$ is a decreasing function, while W_b^{CP} does not depend on f. Furthermore, $W_g^{CP}(0) > W_b^{CP}$. Indeed, write $W_g^{CP} = W_g^{CP}(f,\pi)$ and $\hat{\gamma}_g^{CP} = \hat{\gamma}_g^{CP}(f,\pi)$. Note that W_b^{CP} and $\hat{\gamma}_b^{CP}$ do not depend on f and π. Furthermore, $W_g^{CP}(0,1) = W_b^{CP}$ and $\hat{\gamma}_g^{CP}(0,1) = \hat{\gamma}_b^{CP}$. Suppose that $f = 0$. By the envelope theorem,

$$\frac{dW_g^{CP}(0,\pi)}{d\pi} = \frac{\partial W_g^{CP}(0,\pi)}{\partial \pi} = -\int_0^{\hat{\gamma}_g^{CP}(0,\pi)} \gamma dG(\gamma) - \varepsilon G\left(\hat{\gamma}_g^{CP}(0,\pi)\right)\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}(0,\pi)\right)\right) < 0.$$

Therefore, $W_g^{CP}(0,\pi) \overset{\pi<1}{>} W_g^{CP}(0,1) = W_b^{CP}$. Since $W_g^{CP}(f)$ is a decreasing function, and $W_g^{CP}(0) > W_b^{CP}$, we have $\bar{f}^{CP} > 0$. □

A.4 Corollary 1

Proof. If $\varepsilon = 0$, the expressions in (13) coincide with (5) and (8), that is, $\hat{\gamma}_b^{CP} = \hat{\gamma}_b = \Delta$ and $\hat{\gamma}_g^{CP} = \hat{\gamma}_g = \frac{\Delta - f}{\pi}$. Therefore, conditional on d-firms' adoption decisions, wealth allocation is equivalent in the efficient allocation and in the laissez-faire equilibrium. Under Assumption 3, the highest-welfare equilibrium is played if multiplicity is possible. From Proposition 2, we know that the planner prefers d-firms to adopt the green technology if $f \leq \bar{f}^{CP}$ and prefers d-firms not to adopt the green technology if $f > \bar{f}^{CP}$, where $\bar{f}^{CP}$ is defined in the proof of that proposition. Specifically, if $\varepsilon = 0$, $\bar{f}^{CP}(0)$ solves

$$\bar{f}^{CP}(0) = \Delta \left(1 - \frac{G\left(\hat{\gamma}_b^{CP}\right)}{G\left(\hat{\gamma}_g^{CP}\right)}\right) + \frac{\int_0^{\hat{\gamma}_b^{CP}} \gamma dG - \pi \int_0^{\hat{\gamma}_g^{CP}} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}_g^{CP}\right)},$$

where $\hat{\gamma}_g^{CP} = \hat{\gamma}_g^{CP}(\bar{f}^{CP}(0))$. Furthermore, since $\varepsilon = 0$, $\hat{\gamma}_g^{CP}(\bar{f}^{CP}(0)) = \hat{\gamma}_g(\bar{f}^{CP}(0))$.

To prove the corollary, we need to show that the green equilibrium exists if $f \leq \bar{f}^{CP}(0)$, and the brown equilibrium exists if $f > \bar{f}^{CP}(0)$. It is easy to see that

$$\begin{aligned}\bar{f}^{CP}\left(0\right) =& \Delta \left(1 - \frac{G\left(\hat{\gamma}_b\right)}{G\left(\hat{\gamma}_g\right)}\right) - \frac{\int_{\hat{\gamma}_b}^{\hat{\gamma}_g} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}_g\right)} + \frac{\left(1-\pi\right)\int_0^{\hat{\gamma}_g} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}_g\right)} < \\ & \left(\Delta - \hat{\gamma}_b\right)\left(1 - \frac{G\left(\hat{\gamma}_b\right)}{G\left(\hat{\gamma}_g\right)}\right) + \frac{\left(1-\pi\right)\int_0^{\hat{\gamma}_g} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}_g\right)} = \frac{\left(1-\pi\right)\int_0^{\hat{\gamma}_g} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}_g\right)},\end{aligned}$$

where $\hat{\gamma}_g = \hat{\gamma}_g(\bar{f}^{CP}(0))$. Denote $T_1(f) = f - \frac{(1-\pi)\int_0^{\hat{\gamma}_g(f)} \gamma dG(\gamma)}{G(\hat{\gamma}_g(f))}$. Clearly, $T_1(f)$ is an increasing function. Furthermore, we have just shown that $T_1(\bar{f}^{CP}(0)) < 0$. Therefore, $T_1(f) < 0$ if $f \leq \bar{f}^{CP}(0)$. From (9), it then follows that the green equilibrium exists if $f \leq \bar{f}^{CP}(0)$.

From (6), the brown equilibrium exists if $f > \frac{(1-\pi)\int_0^{\hat{\gamma}_b}\gamma dG(\gamma)}{G(\hat{\gamma}_b)}$. Note that

$$\bar{f}^{CP}(0) - \frac{(1-\pi)\int_0^{\hat{\gamma}_b}\gamma dG(\gamma)}{G(\hat{\gamma}_b)} =$$
$$\Delta\left(1-\frac{G(\hat{\gamma}_b)}{G(\hat{\gamma}_g)}\right) + \frac{\int_0^{\hat{\gamma}_b}\gamma dG}{G(\hat{\gamma}_g)} - \frac{\pi\int_0^{\hat{\gamma}_g}\gamma dG(\gamma)}{G(\hat{\gamma}_g)} - (1-\pi)\frac{\int_0^{\hat{\gamma}_b}\gamma dG}{G(\hat{\gamma}_b)} =$$
$$\Delta\left(1-\frac{G(\hat{\gamma}_b)}{G(\hat{\gamma}_g)}\right) - \frac{\pi\int_{\hat{\gamma}_b}^{\hat{\gamma}_g}\gamma dG(\gamma)}{G(\hat{\gamma}_g)} - (1-\pi)\frac{\int_0^{\hat{\gamma}_b}\gamma dG}{G(\hat{\gamma}_b)}\left(1-\frac{G(\hat{\gamma}_b)}{G(\hat{\gamma}_g)}\right) >$$
$$\left(\bar{f}^{CP}(0) - (1-\pi)\frac{\int_0^{\hat{\gamma}_b}\gamma dG}{G(\hat{\gamma}_b)}\right)\left(1-\frac{G(\hat{\gamma}_b)}{G(\hat{\gamma}_g)}\right),$$

where $\hat{\gamma}_g = \hat{\gamma}_g(\bar{f}^{CP}(0))$. Define $T_2(f) = f - \frac{(1-\pi)\int_0^{\hat{\gamma}_b}\gamma dG(\gamma)}{G(\hat{\gamma}_b)}$. We have just shown that $T_2(\bar{f}^{CP}(0)) > 0$. Furthermore, $T_2(f)$ is an increasing function. Therefore, $T_2(f) > 0$ if $f \geq \bar{f}^{CP}(0)$. Hence, the brown equilibrium exists if $f > \bar{f}^{CP}(0)$. □

A.5 Lemma 2

Proof. Under the green technology adoption subsidy ς^f and the pollution tax τ, investors expecting d-firms to adopt allocate their wealth to d-firms if and only if $\gamma < \hat{\gamma}_g(\tau, \varsigma^f) = \frac{\Delta - (f-\varsigma^f)}{\pi} - \tau$. To implement the green efficient allocation, two conditions need to be met:

$$[\text{Size}]: \ \hat{\gamma}_g(\tau, \varsigma^f) = \hat{\gamma}_g^{CP}, \tag{22}$$
$$[\text{Adoption}]: \ \frac{f-\varsigma^f}{1-\pi} \leq \frac{\int_0^{\hat{\gamma}_g(\tau,\varsigma^f)}\gamma dG(\gamma)}{G(\hat{\gamma}_g(\tau,\varsigma^f))} + \tau, \tag{23}$$

where $\hat{\gamma}_g^{CP}$ is defined in (13). Using (13) and (22), we can derive $\tau = \frac{\varsigma^f}{\pi} + \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$. Combining this with (23), we get

$$\varsigma^f \geq \pi(1-\pi)\left(\frac{f}{1-\pi} - \frac{\int_0^{\hat{\gamma}_g^{CP}}\gamma dG(\gamma)}{G\left(\hat{\gamma}_g^{CP}\right)} - \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)\right). \tag{24}$$

If the right-hand side of the inequality above is nonpositive, the pollution tax $\tau = \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$ alone is sufficient to implement the green efficient allocation. If it is positive, both the pollution tax and the green adoption subsidy are needed. In particular, $\varsigma^f \geq \hat{\varsigma}^f \equiv \max[0, T]$, where T is the right-hand side of (24). □

A.6 Lemma 3

Proof. Welfare in the green and brown equilibria can be written as

$$W_g(\tau) = \alpha_c + G(\hat{\gamma}_g(\tau))(\Delta - f) - \pi \int_0^{\hat{\gamma}_g(\tau)} \gamma dG(\gamma) - \varepsilon\xi(\pi G(\hat{\gamma}_g(\tau))),$$
$$W_b(\tau) = \alpha_c + G(\hat{\gamma}_b(\tau))\Delta - \int_0^{\hat{\gamma}_b(\tau)} \gamma dG(\gamma) - \varepsilon\xi(G(\hat{\gamma}_b(\tau))),$$

where $\hat{\gamma}_b(\tau)$ and $\hat{\gamma}_g(\tau)$ are given by (14) under $\varsigma^f = 0$. Differentiating $W_g(\tau)$ and $W_b(\tau)$ with respect to τ, we find

$$\frac{dW_g}{d\tau} = -\pi g(\hat{\gamma}_g(\tau))(\tau - \varepsilon\xi'(\pi G(\hat{\gamma}_g(\tau)))), \tag{25}$$
$$\frac{dW_b}{d\tau} = -g(\hat{\gamma}_b(\tau))(\tau - \varepsilon\xi'(G(\hat{\gamma}_b(\tau)))). \tag{26}$$

Setting the derivatives (25)–(26) to zero, we find

$$\tau_g^* - \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g\left(\tau_g^*\right)\right)\right) = 0, \tag{27}$$
$$\tau_b^* - \varepsilon\xi'\left(G\left(\hat{\gamma}_b\left(\tau_b^*\right)\right)\right) = 0. \tag{28}$$

Since $\xi(\cdot)$ is an increasing convex function such that $\xi(0) = \xi'(0) = 0$, there exists a unique solution to (27), $\tau_g^* \in \left(0, \frac{\Delta - f}{\pi}\right)$, because the left-hand side of this equation is an increasing function that switches sign on $\left(0, \frac{\Delta - f}{\pi}\right)$. Similarly, there exists a unique $\tau_b^* \in (0, \Delta)$ solving (28). Furthermore, $\tau_g^* = \tau_g^*(\varepsilon)$ and $\tau_b^* = \tau_b^*(\varepsilon)$ are increasing functions of ε because the left-hand sides of (27)–(28) decrease in ε.

At these tax levels, firm sizes are the same as in the efficient allocation, i.e., $\hat{\gamma}_b(\tau_b^*) = \hat{\gamma}_b^{CP}$ and $\hat{\gamma}_g\left(\tau_g^*\right) = \hat{\gamma}_g^{CP}$, where $\hat{\gamma}_b(\tau)$ and $\hat{\gamma}_g(\tau)$ are given by (14) under $\varsigma^f = 0$, and $\hat{\gamma}_b^{CP}$ and $\hat{\gamma}_g^{CP}$ are given by (13). We then have $W_g\left(\tau_g^*\right) = W_g^{CP}$ and $W_b(\tau_b^*) = W_b^{CP}$. Therefore, by Proposition 2, $W_g\left(\tau_g^*(\varepsilon)\right) > W_b(\tau_b^*(\varepsilon))$ if and only if $f < \bar{f}^{CP}$. □

A.7 Proposition 3

Proof. We start by proving that the green equilibrium exists for a sufficiently large and small values of τ. By Proposition 1, the green equilibrium exists if $\Delta \geq \underline{\Delta} > \frac{f}{1-\pi}$,

$f < (1-\pi)\int_0^{\bar{\gamma}} \gamma dG(\gamma)$, and $\tau = 0$, i.e.,

$$\psi^{\tau}\left(\hat{\gamma}_g(0), 0\right) = \frac{\int_0^{\hat{\gamma}_g(0)} \gamma dG(\gamma)}{G\left(\hat{\gamma}_g(0)\right)} \geq \frac{f}{1-\pi},$$

where $\psi^{\tau}(\hat{\gamma}, \tau)$ is defined in (16), and $\hat{\gamma}_g(\tau)$ is given by (14) under $\varsigma^f = 0$. Because $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right)$ is a continuous function of τ, it then follows that there exists $\underline{\tau} \geq 0$ such that $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right) \geq \frac{f}{1-\pi}$ on $\tau \in [0, \underline{\tau}]$.

Next, note that if $\tau \in \left[\frac{f}{1-\pi}, \frac{\Delta - f}{\pi}\right)$, the green equilibrium exists. This is because d-firms raise nonzero capital, $\hat{\gamma}_g(\tau) > 0$, and d-firms' managers find it optimal to pay the adoption cost, i.e., $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right) \geq \frac{f}{1-\pi}$. Furthermore, at $\tau = \frac{f}{1-\pi}$, $\hat{\gamma}_g\left(\frac{f}{1-\pi}\right) = \frac{\Delta(1-\pi)-f}{\pi(1-\pi)} > 0$ and $\psi^{\tau}\left(\hat{\gamma}_g\left(\frac{f}{1-\pi}\right), \frac{f}{1-\pi}\right) > \frac{f}{1-\pi}$, and, by continuity, there exists a $\bar{\tau} < \frac{f}{1-\pi}$ such that the green equilibrium exists on $\tau \in \left[\bar{\tau}, \frac{\Delta - f}{\pi}\right)$.

We proceed to show that the green equilibrium might not exist for some intermediate range of τ. The green equilibrium does not exist if $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right) < \frac{f}{1-\pi}$. Define set $\mathcal{S}_{\tau}^{g} = \left\{\tau : \psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right) < \frac{f}{1-\pi}\right\}$. Since $\psi^{\tau}\left(\hat{\gamma}_g(\tau), \tau\right)$ is a smooth function of τ, $\mathcal{S}_{\tau}^{g}$ is a countable union of disjoint open intervals, i.e., $\mathcal{S}_{\tau}^{g} = \bigcup_{i=1}^{N} (\underline{\tau}_i, \bar{\tau}_i)$, where $\frac{f}{1-\pi} > \bar{\tau}_N > \underline{\tau}_N > \cdots > \underline{\tau}_1 \geq \underline{\tau}$, such that the green equilibrium does not exist if and only if $\tau \in \mathcal{S}_{\tau}^{g}$. To show that this set is generally nonempty, suppose that $\Delta = \underline{\Delta}$. Then, by definition of $\underline{\Delta}$, $\psi^{\tau}\left(\hat{\gamma}_g(0, \underline{\Delta}), 0\right) = \frac{f}{1-\pi}$, where we write $\hat{\gamma}_g$ as a function of τ and Δ, i.e., $\hat{\gamma}_g = \hat{\gamma}_g(\tau, \Delta)$. If $\frac{d\psi^{\tau}}{d\tau}\big|_{\tau=0} < 0$, then a marginal increase in τ from 0 implies that the green equilibrium ceases to exist. Then the set $\mathcal{S}_{\tau}^{g}$ takes the form as conjectured in the proposition because $\psi^{\tau}\left(\hat{\gamma}_g(\tau, \Delta), \tau\right)$ is a smooth function of τ and Δ.

We now show that the brown equilibrium exists if the green equilibrium does not. Note that $\hat{\gamma}_g(\tau) > \hat{\gamma}_b(\tau) \Leftrightarrow \Delta > \frac{f}{1-\pi}$, which is true because $\Delta \geq \underline{\Delta} > \frac{f}{1-\pi}$. Here $\hat{\gamma}_b(\tau)$ and $\hat{\gamma}_g(\tau)$ are given by (14) under $\varsigma^f = 0$. Therefore, if the green equilibrium does not exist, i.e., $\psi^{\tau}(\hat{\gamma}_g(\tau), \tau) < \frac{f}{1-\pi}$, then the brown equilibrium exists because $\psi^{\tau}(\hat{\gamma}, \tau)$ is an increasing function of $\hat{\gamma}$ and so $\psi^{\tau}(\hat{\gamma}_b(\tau), \tau) < \psi^{\tau}(\hat{\gamma}_g(\tau), \tau) < \frac{f}{1-\pi}$.

We are left to conduct the comparative statics of capital raised by d-firms, output, and pollution with respect to τ. Capital raised by d-firms in the green equilibrium is

$K_{d,g} = G(\hat{\gamma}_g(\tau)) \Rightarrow \frac{dK_{d,g}}{d\tau} = -g(\hat{\gamma}_g(\tau)) < 0$, and in the brown equilibrium is $K_{d,b} = G(\hat{\gamma}_b(\tau)) \Rightarrow \frac{dK_{d,b}}{d\tau} = -g(\hat{\gamma}_b(\tau)) < 0$. The negative impact of τ on capital raised by d-firms implies that pollution in the green and brown equilibria decline in τ because $P_g = \pi K_{d,g}$ and $P_b = K_{d,b}$, respectively. Output in the green and brown equilibria also decline in τ because $Y_g = \alpha_c + K_{d,g}(\Delta - f)$ and $Y_b = \alpha_c + K_{d,b}\Delta$, respectively. Note that if the green equilibrium exists, it must be that $\hat{\gamma}_g > 0 \Rightarrow \Delta > f$. □

A.8 Proposition 4 and Corollary 2

Proof. Recall that $\tau_g^*(\varepsilon)$ solves (27). From that equation, it is immediate that $\tau_g^*(\varepsilon)$ is a continuous and increasing function.

By Proposition 3, if $\tau_g^*(\varepsilon) \notin \mathcal{S}_\tau^g$, then the green equilibrium exists at $\tau = \tau_g^*(\varepsilon)$. Part (i) of Proposition 4 then follows because $\tau_g^*(\varepsilon)$ is an increasing function of ε.

Suppose now that $\tau_g^*(\varepsilon) \in \mathcal{S}_\tau^g$, i.e., $\tau_g^*(\varepsilon) \in (\underline{\tau}_i, \bar{\tau}_i)$ for some i. From (25), $W_g(\tau)$ is maximized at $\tau_g^*(\varepsilon)$, and $\frac{dW_g}{d\tau} > 0$ if $\tau < \tau_g^*(\varepsilon)$ and $\frac{dW_g}{d\tau} < 0$ if $\tau > \tau_g^*(\varepsilon)$. Therefore, the tax that sustains the green equilibrium and yields the highest welfare at this level of ε is either $\underline{\tau}_i$ or $\bar{\tau}_i$.

Finally, note that $\frac{\partial W_g(\tau)}{\partial \varepsilon} = -\xi(\pi G(\hat{\gamma}_g(\tau))) < 0$. Since $\hat{\gamma}_g(\tau)$ is a decreasing function, we have $\frac{\partial W_g(\underline{\tau}_i)}{\partial \varepsilon} < \frac{\partial W_g(\bar{\tau}_i)}{\partial \varepsilon}$. By definitions of $\bar{\tau}_i$ and $\underline{\tau}_i$, we have $W_g(\bar{\tau}_i) > W_g(\underline{\tau}_i)$ when $\varepsilon = \bar{\varepsilon}_i$, and $W_g(\bar{\tau}_i) < W_g(\underline{\tau}_i)$ when $\varepsilon = \underline{\varepsilon}_i$. Therefore, if $\varepsilon \in (\underline{\varepsilon}_i, \bar{\varepsilon}_i)$, then there exists $\varepsilon_i^s \in (\underline{\varepsilon}_i, \bar{\varepsilon}_i)$ such that $\tau^*(\varepsilon) = \underline{\tau}_i$ if $\varepsilon \in (\underline{\varepsilon}_i, \varepsilon_i^s]$ and $\tau^*(\varepsilon) = \bar{\tau}_i$ if $\varepsilon \in (\varepsilon_i^s, \bar{\varepsilon}_i)$. □

A.9 Lemma 4

Proof. Fix $\hat{\gamma} \in (0, \bar{\gamma})$. The shareholder-base effect is weak at $\hat{\gamma}$ if (17) is positive, i.e.,

$$\frac{g(\hat{\gamma})}{G(\hat{\gamma})}\left(\hat{\gamma} - \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G(\hat{\gamma})}\right) < 1.$$

Computing the left-hand side under (19), we get

$$A(x) = \frac{a\left(wx^{a-1}+(1-w)(1-x)^{a-1}\right)\left(w\frac{x^{a+1}}{a+1}+(1-w)\left(x-\frac{1}{a+1}\left(1-(1-x)^{a+1}\right)\right)\right)}{\left(wx^{a}+(1-w)\left(1-(1-x)^{a}\right)\right)^{2}}, \tag{29}$$

where $x = \frac{\hat{\gamma}}{\bar{\gamma}} \in (0,1)$.

Evaluating (29) at $a = 1$, we get $A(x, a = 1) = \frac{1}{2}$. Since $A(x, a)$ is continuous in a, we conclude that there exists an $\underline{a} > 1$ such that $A(x, a) < 1$ for any $a < \underline{a}$. This proves part (i) of the lemma.

Evaluating (29) at $w = 0$, we get

$$A(x, w = 0) = \frac{a(1-x)^{a-1}\left(x-\frac{1}{a+1}\left(1-(1-x)^{a+1}\right)\right)}{\left(1-(1-x)^{a}\right)^{2}} \overset{t=(1-x)^{a}}{=} \frac{a\left(\frac{a}{a+1}t^{\frac{a-1}{a}}-t+\frac{1}{a+1}t^{2}\right)}{(1-t)^{2}}$$

$$\leq \frac{a\left(\frac{a}{a+1}\left(1+\frac{a-1}{a}(t-1)\right)-t+\frac{1}{a+1}t^{2}\right)}{(1-t)^{2}} = \frac{a}{a+1} < 1,$$

where the inequality holds because $t^{\frac{a-1}{a}}$ is a concave function under $a > 1$. Next, evaluating (29) at $w = 1$, we immediately get $A(x, w = 1) = \frac{a}{a+1} < 1$. Since $A(x, w = 0), A(x, w = 1) < 1$ and $A(x, w)$ is continuous in w, it follows that there exist $1 > \bar{w} \geq \underline{w} > 0$ such that $A(x, w) < 1$ if $w < \underline{w}$ or $w > \bar{w}$. This proves part (ii) of the lemma.

Finally, we need to show that for a given $w \in (0,1)$, there exists an $\bar{a}$ such that if $a > \bar{a}$, (29) is above 1 for some $x \in (0,1)$. Evaluating (29) at $x = 1$, we get $A(1) = aw\left(w\frac{1}{a+1}+(1-w)\frac{a}{a+1}\right)$. It is easy to see that this expression is increasing in a. Since $A(x, a)$ is continuous in x, we conclude that there exists an $\bar{a}$ such that for each $a > \bar{a}$, $A(x, a) > 1$ for x close to 1. □

A.10 Lemma 5

Proof. Welfare in the green and brown equilibria can be written as

$$W_g(\varsigma) = \alpha_c + G(\hat{\gamma}_g(\varsigma))(\Delta - f) - \pi \int_0^{\hat{\gamma}_g(\varsigma)} \gamma dG(\gamma) - \varepsilon\xi(\pi G(\hat{\gamma}_g(\varsigma))),$$
$$W_b(\varsigma) = \alpha_c + G(\hat{\gamma}_b(\varsigma))\Delta - \int_0^{\hat{\gamma}_b(\varsigma)} \gamma dG(\gamma) - \varepsilon\xi(G(\hat{\gamma}_b(\varsigma))), \tag{30}$$

where $\hat{\gamma}_b(\varsigma) = \Delta - \varsigma$ and $\hat{\gamma}_g(\varsigma) = \frac{\Delta-\varsigma-f}{\pi}$. Differentiating with respect to ς, we find

$$\frac{dW_g}{d\varsigma} = -\frac{1}{\pi} g(\hat{\gamma}_g(\varsigma))(\varsigma - \pi\varepsilon\xi'(\pi G(\hat{\gamma}_g(\varsigma)))),$$
$$\frac{dW_b}{d\varsigma} = -g(\hat{\gamma}_b(\varsigma))(\varsigma - \varepsilon\xi'(G(\hat{\gamma}_b(\varsigma)))).$$

Setting the derivatives to zero, we find

$$\varsigma_g^* - \pi\varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g\left(\varsigma_g^*\right)\right)\right) = 0, \tag{31}$$
$$\varsigma_b^* - \varepsilon\xi'\left(G\left(\hat{\gamma}_b\left(\varsigma_b^*\right)\right)\right) = 0. \tag{32}$$

Recall that the externality function $\xi(\cdot)$ is an increasing convex function such that $\xi(0) = \xi'(0) = 0$. Then there exists a unique solution to (31), $\varsigma_g^* \in (0, \Delta - f)$ because the left-hand side of this equation is an increasing function that switches sign on $(0, \Delta - f)$. Similarly, there exists a unique $\varsigma_b^* \in (0, \Delta)$ solving (32). Furthermore, $\varsigma_g^* = \varsigma_g^*(\varepsilon)$ and $\varsigma_b^* = \varsigma_b^*(\varepsilon)$ are increasing functions of ε because the left-hand sides of (31)–(32) decrease in ε. Finally, $\varsigma_g^*(\varepsilon) < \varsigma_b^*(\varepsilon)$ because, $\xi(\cdot)$ is a convex function and, by Assumption 2, pollution in the green equilibrium is lower than in the brown equilibrium for a given level of subsidy, i.e., $\pi G(\hat{\gamma}_g(\varsigma)) < G(\hat{\gamma}_b(\varsigma))$. □

A.11 Proposition 5

Proof. See Online Appendix C.5.1. □

A.12 Lemma 6

Proof. Under the subsidy to c-firms ς and the pollution tax τ, investors expecting d-firms to adopt allocate their wealth to d-firms if and only if $\gamma < \hat{\gamma}_g(\tau, \varsigma) = \frac{\Delta-\varsigma-f}{\pi} - \tau$. To

implement the green efficient allocation, two conditions need to be met:

$$[\text{Size}]: \ \hat{\gamma}_g(\tau,\varsigma) = \hat{\gamma}_g^{CP}, \tag{33}$$

$$[\text{Adoption}]: \ \frac{f}{1-\pi} \leq \frac{\int_0^{\hat{\gamma}_g(\tau,\varsigma)} \gamma dG(\gamma)}{G\left(\hat{\gamma}_g(\tau,\varsigma)\right)} + \tau, \tag{34}$$

where $\hat{\gamma}_g^{CP}$ is defined in (13). Using (13) and (33), we can derive $\tau = -\frac{\varsigma}{\pi} + \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$. Combining this with (34), we get

$$\varsigma \leq \pi\left(\frac{\int_0^{\hat{\gamma}_g^{CP}} \gamma dG(\gamma)}{G\left(\hat{\gamma}_g^{CP}\right)} - \frac{f}{1-\pi} + \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)\right). \tag{35}$$

If the right-hand side of the inequality above is nonnegative, the pollution tax $\tau = \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$ alone is sufficient to implement the green efficient allocation. If it is negative, both the pollution tax and the subsidy are needed. In particular, $\varsigma \leq \hat{\varsigma} \equiv \min[0, T]$, where T is the right-hand side of (35). □

B Parametrizations used in figures

Figures 2, 3, 4, 7, and 8: $\alpha_d = 1.6$, $\alpha_c = 1$, $\pi = 0.3$, $f = 0.275$. Distribution of γ: $\bar{\gamma} = 1.1$, $G(\gamma)$ is given by (19), with $w = 0.5$ and $a = 10$. For Figure 3, the externality function is $\xi(x) = \frac{1}{4}x^4$, $\varepsilon = 25$. In Figure 4, ε varies from 1 to 80.

Figures 6: $\alpha_d = 1.5$, $\alpha_c = 1$, $\pi = 0.55$, $f = 0.09$, externality function is $\xi(x) = \frac{1}{2}x^2$, distribution of γ is uniform on $[0, 1]$. Panel (A): $\varepsilon = 1$; panel (B): $\varepsilon = 3$; panel (C): $\varepsilon = 4.5$.

Online Appendix

C Additional analyses

C.1 Borrowing and lending

In the baseline model, investors are not allowed to borrow. Suppose that investors can borrow from and lend to each other. We assume that if an investor is indifferent between lending and investing in c- or d-firms by herself, she prefers the latter option. Then, if there is any lending in equilibrium, the lending rate R must exceed α_c. If $R \leq \alpha_c$, no one lends in equilibrium because investing in c-firms is a dominating option. Since $R > \alpha_c$, shareholders of c-firms never borrow in equilibrium. Therefore, each lender understands that the money she lends will be invested in d-firms. Consequently, for an investor γ, lending one dollar is associated with the utility

$$v_R(\gamma, \mathsf{a}_d) = R - \gamma\left(\pi + (1-\pi)\mathbb{1}_{\{\mathsf{a}_d=0\}}\right).$$

Therefore, if $R \leq \alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}}$, each investor prefers investing in d-firms to lending because $v_R(\gamma, \mathsf{a}_d) \leq v_d(\gamma, \mathsf{a}_d)$, where $v_d(\gamma, \mathsf{a}_d)$ is given by (1). On the other hand, if $R > \alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}}$, none of the investors wants to borrow.

Consequently, assuming no borrowing in the baseline model is innocuous. Notably, this result relies on the assumption that investors suffer the same disutility from investing in d-firms by themselves and lending their money to other investors who then invest in d-firms. If investors are naive, in the sense that investing money in d-firms through other investors is associated with a lower disutility, then borrowing can arise in equilibrium.

C.2 Green and brown equilibria: Comparison

Lemma 7. *There exists a threshold $\bar{f} = \bar{f}(\varepsilon) > 0$ such that the green equilibrium exists and is socially preferable, $W_g > W_b$, if $f < \bar{f}$. Moreover, $\bar{f}(\varepsilon)$ is a (weakly) increasing function.*

Proof. Define f^1 implicitly as a solution to $\frac{f}{1-\pi} - \frac{\int_0^{\hat{\gamma}_g(f)} \gamma dG(\gamma)}{G(\hat{\gamma}_g(f))} = 0$, where we write $\hat{\gamma}_g$,

defined by (8), as a function of f. Clearly, there exists a unique $f > 0$ solving this equation because the left-hand side is an increasing function that is negative at $f = 0$ and positive as f approaches Δ (and, hence, $\hat{\gamma}_g(f)$ approaches zero). The green equilibrium exists if $f \in [0, f^1]$.

Next, we compare welfare in the green and brown equilibria. They are given by (7) and (11), respectively, and can be written as

$$W_b = W_b^1 - \varepsilon\xi\left(G\left(\hat{\gamma}_b\right)\right) = \alpha_c + G\left(\hat{\gamma}_b\right)\Delta - \int_0^{\hat{\gamma}_b} \gamma dG(\gamma) - \varepsilon\xi\left(G\left(\hat{\gamma}_b\right)\right),$$
$$W_g = W_g^1 - \varepsilon\xi\left(\pi G\left(\hat{\gamma}_g\right)\right) = \alpha_c + G\left(\hat{\gamma}_g\right)(\Delta - f) - \pi\int_0^{\hat{\gamma}_g} \gamma dG(\gamma) - \varepsilon\xi\left(\pi G\left(\hat{\gamma}_g\right)\right),$$

where $\hat{\gamma}_b$ and $\hat{\gamma}_g$ are given by (5) and (8), respectively. Write $\hat{\gamma}_g = \hat{\gamma}_g(f, \pi)$, $W_g^1 = W_g^1(f, \pi)$ and $W_g = W_g(f, \pi)$ as functions of f and π. Note that $\hat{\gamma}_b$, W_b^1 and W_b do not depend on f and π.

Suppose that $f = 0$. Differentiating W_g^1 with respect to π, we find $\frac{dW_g^1(0,\pi)}{d\pi} = -\int_0^{\hat{\gamma}_g(0,\pi)} \gamma dG(\gamma) < 0$. Therefore,

$$\begin{aligned} W_g(0,\pi) =& W_g^1(0,\pi) - \varepsilon\xi\left(\pi G\left(\hat{\gamma}_g(0,\pi)\right)\right) \overset{\pi<1}{>} W_g^1(0,1) - \varepsilon\xi\left(\pi G\left(\hat{\gamma}_g(0,\pi)\right)\right) = \\ & W_1^b - \varepsilon\xi\left(\pi G\left(\hat{\gamma}_g(0,\pi)\right)\right) \overset{\text{Asm } 2}{>} W_1^b - \varepsilon\xi\left(G\left(\hat{\gamma}_b\right)\right) = W^b. \end{aligned} \tag{36}$$

Consider the range of f for which the green equilibrium exists, i.e., $f \in [0, f^1]$. Define $\bar{f} = f^1$ if $W_g(f) \geq W_b \ \forall f \in [0, f^1]$. In this case, $\bar{f}$ does not depend on ε.

If $\exists \check{f} \in [0, f^1]$ such that $W_g(\check{f}) < W_b$, then define $\bar{f} = \inf\{f \in [0, f^1] : W_g(f) < W_b\}$. In this case, $\bar{f} > 0$ because $W_g(f)$ is a continuous function and $W_g(0) > W_b$ by (36).

Finally, we prove that $\frac{d\bar{f}}{d\varepsilon} > 0$. Given the definition of $\bar{f}$, we obtain

$$W_g\left(\bar{f}, \varepsilon\right) - W_b(\varepsilon) = 0 \Rightarrow \left.\frac{\partial W_g}{\partial f}\right|_{f=\bar{f}} \times \frac{d\bar{f}}{d\varepsilon} + \frac{\partial W_g}{\partial \varepsilon} - \frac{\partial W_b}{\partial \varepsilon} = 0. \tag{37}$$

Note that $\frac{\partial W_g}{\partial \varepsilon} - \frac{\partial W_b}{\partial \varepsilon} = \xi\left(G\left(\hat{\gamma}_b\right)\right) - \xi\left(\pi G\left(\hat{\gamma}_g\right)\right) > 0$ by Assumption 2. Furthermore, since $\bar{f}$ is an infimum, $\left.\frac{\partial W_g}{\partial f}\right|_{f=\bar{f}} < 0$. From (37) it then follows that $\frac{d\bar{f}}{d\varepsilon} > 0$. □

C.3 Green preferences and pollution

Lemma 8. *Pollution is highest if investors do not have green preferences, i.e., if* $\gamma = 0$ *for all investors. However, if investors have green preferences, i.e.,* $\gamma > 0$ *for some investors, pollution can increase if the green preferences of all investors strengthen.*

Proof. Clearly, pollution reaches its maximum if c-firms receive no capital and d-firms do not adopt the green technology. This is the case if $\gamma = 0$ for all investors.

Next, suppose that investors have green preferences, i.e., $\gamma > 0$ for some investors. Furthermore, suppose that the green equilibrium exists and $f < \bar{f}$, where $\bar{f}$ is defined in Lemma 7. Then the green equilibrium is played by Assumption 3. In the remainder of this proof, we show that if the strength of green preferences of all investors increases, the green equilibrium may cease to exist. Therefore, by Assumption 2, pollution increases.

Specifically, suppose that $\psi(\hat{\gamma}_g) \equiv \frac{\int_0^{\hat{\gamma}_g} \gamma dG(\gamma)}{G(\hat{\gamma}_g)} = \frac{f}{1-\pi}$, where $\hat{\gamma}_g$ is given by (8). Since condition (9) is satisfied, the green equilibrium exists. Suppose that the strength of green preferences increases for all investors by a factor of $\chi \geq 1$. Then $\psi(\hat{\gamma}_g)$ becomes $\psi(\hat{\gamma}_g, \chi) = \frac{\chi \int_0^{\frac{\hat{\gamma}_g}{\chi}} \gamma dG(\gamma)}{G\left(\frac{\hat{\gamma}_g}{\chi}\right)}$. Differentiating it with respect to χ at $\chi = 1$, we get

$$\left.\frac{\partial \psi}{\partial \chi}\right|_{\chi=1} = \frac{\int_0^{\hat{\gamma}_g} \gamma dG(\gamma)}{G(\hat{\gamma}_g)} - \frac{\hat{\gamma}_g g(\hat{\gamma}_g)}{G(\hat{\gamma}_g)} \left(\hat{\gamma}_g - \frac{\int_0^{\hat{\gamma}_g} \gamma dG(\gamma)}{G(\hat{\gamma}_g)}\right).$$

This derivative is negative if $g(\hat{\gamma}_g)$ is sufficiently high, that is, if there are many investors whose green preferences are at the threshold $\hat{\gamma}_g$. A marginal increase in the strength of green preferences (i.e., a χ slightly above 1) means that these investors switch from being d-firms' shareholders to becoming c-firms' shareholders. As a result, the average green preferences of remaining d-firms' shareholders weaken significantly, and condition (9) is no longer satisfied. Consequently, the green equilibrium ceases to exist, and only the brown equilibrium is possible. We finish this proof with an example in which the aforementioned effects are at play.

Suppose that the distribution $g(\gamma)$ of investor types is two-peaked, as shown in panel (A) of Figure 8. The first group consists of investors who are highly concerned about

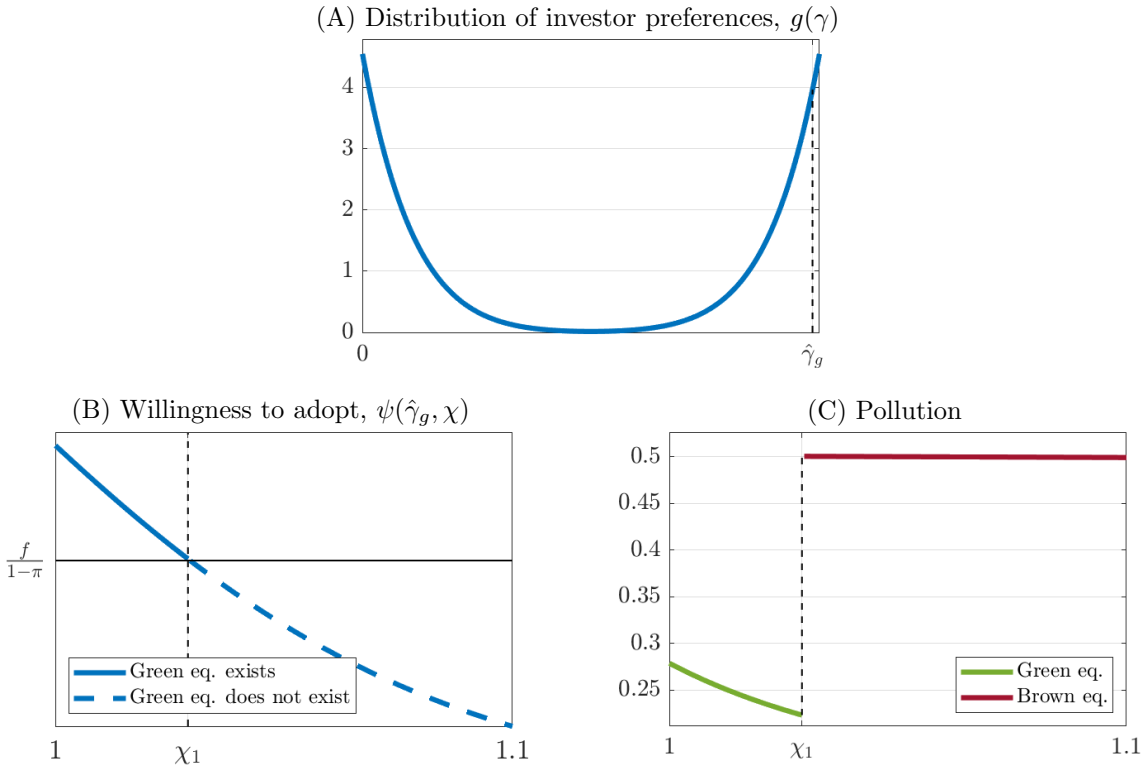


Figure 8: Panel (A): Probability density function of the distribution of investor preferences, $g(\gamma)$, at $\chi = 1$. Panel (B): Willingness to adopt the green technology, $\psi(\hat{\gamma}_g, \chi)$, as χ changes from 1 to 1.1; green equilibrium exists if and only if $\psi(\hat{\gamma}_g, \chi) \geq \frac{f}{1-\pi}$. Panel (C): Pollution as χ changes from 1 to 1.1. Appendix B provides numerical values used for these graphs.

the greenness of their portfolios (right peak). The second group consists of investors who mostly care about the financial performance of their portfolios (left peak). When $\chi = 1$, a marginal investor $\hat{\gamma}_g$ belongs to the first group, as shown in panel (A). At this point, the willingness of d-firms to adopt the green technology is sufficiently strong, $\psi(\hat{\gamma}_g, 1) > \frac{f}{1-\pi}$ (panel (B) in the same figure), and the green equilibrium exists.

An increase in χ implies that many investors with strong green preferences switch from being shareholders of d-firms to being shareholders of c-firms. Even though remaining d-firms' shareholders become more concerned about the greenness of their portfolios due to an increase in χ, the exodus of a large group of investors with strong green preferences dominates. As shown in panel (B), the overall willingness to adopt the green technology for d-firms declines, i.e., $\psi(\hat{\gamma}_g, \chi)$ declines in χ. If χ reaches $\chi_1 > 1$, the average preferences of d-firms' shareholders weaken to the point that they are no longer willing to adopt the green technology. The green equilibrium ceases to exist, which im-

plies an increase in pollution due to the switch to the brown equilibrium (panel (C) in the same figure). □

C.4 Investor composition and shareholder-base effect

Suppose that the investor preference distribution is given by (19). Figure 9 shows the threshold $\hat{a}(w)$, such that the shareholder-base effect is weak (that is, (17) is positive for any $\gamma \in (0, \bar{\gamma})$) if and only if $a < \hat{a}(w)$.

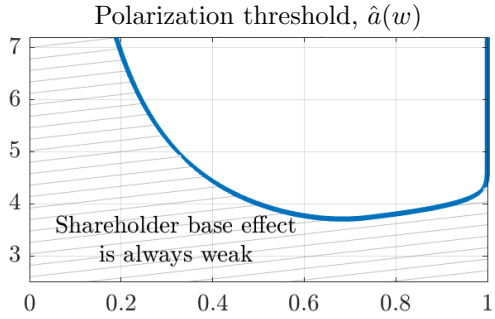


Figure 9: Threshold $\hat{a}(w)$ as a function of the mixture weight w in (19). Shareholder-base effect is always weak if and only if $a < \hat{a}(w)$.

C.5 Subsidy to clean firms

At the beginning of $t = 1$, before investors make their portfolio choices, the regulator imposes a subsidy $\varsigma \geq 0$. Specifically, the regulator commits to transfer ςk_c to each c-firm at $t = 2$, where k_c is the amount of capital a c-firm raises from investors. The subsidy is financed by lump sum taxation of all investors. Effectively, the subsidy makes c-firms more financially attractive by reducing the difference between the productivities of firms of different types: without the subsidy, this difference is Δ; under the subsidy, it is $\Delta - \varsigma$.

The equilibrium characterization is analogous to that of the baseline model in Section 3.1. The main difference is that a marginal investor, who is indifferent between holding shares of c- and d-firms, is less concerned about the greenness of her portfolio in any equilibrium in the presence of the subsidy, i.e.,

$$\hat{\gamma}_b(\varsigma) = \Delta - \varsigma, \tag{38}$$

$$\hat{\gamma}_g(\varsigma) = \frac{\Delta - \varsigma - f}{\pi}. \tag{39}$$

Adoption criterion for d-firms (3), output Y, pollution P, and welfare W remain unchanged for both equilibria, where in this section we define output as the overall firms' output net of taxes imposed on investors.

We characterize how the subsidy size ς reshapes the regions in which the two equilibria exist and equilibrium quantities.

Proposition 6. *Then there exist* $0 \leq \underline{\varsigma} < \bar{\varsigma} < \Delta - f$ *such that*

(i) if $\varsigma \leq \underline{\varsigma}$*, only the green equilibrium exists;*

(ii) if $\varsigma > \bar{\varsigma}$*, only the brown equilibrium exists;*

(iii) if $\varsigma \in (\underline{\varsigma}, \bar{\varsigma}]$*, the green and brown equilibria coexist.*

Furthermore, in any equilibrium, an increase in ς *leads to reductions in the amount of capital raised by d-firms, aggregate output, and pollution.*

Proof. Introducing subsidy to c-firms affects only the preference of a marginal investor, $\hat{\gamma}_b(\varsigma)$ and $\hat{\gamma}_g(\varsigma)$ in the brown and green equilibria, respectively. They are given by (38) and (39). From (38) and (39), it follows that increasing ς is equivalent to reducing Δ. Therefore, the existence of $\underline{\varsigma}$ and $\bar{\varsigma}$, defined in Proposition 6, directly follows from Proposition 1. Specifically, $\underline{\varsigma} = \Delta - \bar{\Delta}$ and $\bar{\varsigma} = \Delta - \underline{\Delta}$. Note that at $\varsigma = \varsigma_1 \equiv \Delta - f$ the green equilibrium does not exist because $\hat{\gamma}_g(\varsigma_1) = 0$. Therefore, $\bar{\varsigma} < \varsigma_1 = \Delta - f$.

We proceed by conducting the comparative statics of capital raised by d-firms, output, and pollution with respect to ς. Capital raised by d-firms in the green equilibrium is $K_{d,g} = G(\hat{\gamma}_g(\varsigma)) \Rightarrow \frac{dK_{d,g}}{d\varsigma} = -g(\hat{\gamma}_g(\varsigma))\frac{1}{\pi} < 0$, and in the brown equilibrium is $K_{d,b} = G(\hat{\gamma}_b(\varsigma)) \Rightarrow \frac{dK_{d,b}}{d\varsigma} = -g(\hat{\gamma}_b(\varsigma)) < 0$. The negative impact of ς on capital raised by d-firms implies that pollution in the green and brown equilibria decline in ς because $P_g = \pi K_{d,g}$ and $P_b = K_{d,b}$, respectively. Output in the green and brown equilibria also decline in ς because $Y_g = \alpha_c + K_{d,g}(\Delta - f)$ and $Y_b = \alpha_c + K_{d,b}\Delta$, respectively. Note that if the green equilibrium exists, it must be that $\hat{\gamma}_g > 0 \Rightarrow \Delta > f$. □

C.5.1 Proof of Proposition 5

Proof. Recall that $\varsigma_g^*(\varepsilon)$ and $\varsigma_b^*(\varepsilon)$ solve (31) and (32), respectively. Using the definitions of $\hat{\gamma}_b(\varsigma) = \Delta - \varsigma$ and $\hat{\gamma}_g(\varsigma) = \frac{\Delta - \varsigma - f}{\pi}$, we find

$$\begin{aligned} \varsigma_g^*(0) = 0, \quad \lim_{\varepsilon \to \infty} \varsigma_g^*(\varepsilon) = \Delta - f, \\ \varsigma_b^*(0) = 0, \quad \lim_{\varepsilon \to \infty} \varsigma_b^*(\varepsilon) = \Delta. \end{aligned} \tag{40}$$

Furthermore, by Lemma 5, $\varsigma_g^*(\varepsilon)$ and $\varsigma_b^*(\varepsilon)$ are increasing functions. Therefore, there exists a unique $\underline{\varepsilon}^{\varsigma}$ such that $\varsigma_g^*\left(\underline{\varepsilon}^{\varsigma}\right) = \bar{\varsigma}$, where $\bar{\varsigma}$ is defined in Proposition 6.

If $\varepsilon \leq \underline{\varepsilon}^{\varsigma}$, the green equilibrium exists under the subsidy level $\varsigma_g^*(\varepsilon)$ because $\varsigma_g^*(\varepsilon) < \bar{\varsigma}$.

Next, we characterize the optimal subsidy when $\varepsilon > \underline{\varepsilon}^{\varsigma}$. In this case, $\varsigma_g^*(\varepsilon) > \bar{\varsigma}$, and the highest welfare in the green equilibrium is reached at $\bar{\varsigma}$ because $W_g(\varsigma)$ increases on $\varsigma \in [0, \bar{\varsigma}]$. Thus, the regulator either chooses $\bar{\varsigma}$ such that the green equilibrium is played, or $\varsigma_b^*(\varepsilon)$ to achieve the highest welfare in the brown equilibrium, $W_b\left(\varsigma_b^*(\varepsilon)\right)$. At $\varsigma = \bar{\varsigma}$, welfare in the green equilibrium is

$$W_g(\bar{\varsigma}) = \alpha_c + G\left(\hat{\gamma}_g(\bar{\varsigma})\right)(\Delta - f) - \pi \int_0^{\hat{\gamma}_g(\bar{\varsigma})} \gamma dG(\gamma) - \varepsilon \xi\left(\pi G\left(\hat{\gamma}_g(\bar{\varsigma})\right)\right). \tag{41}$$

Define

$$\bar{\varepsilon}^{\varsigma} = \inf\{\varepsilon \geq \underline{\varepsilon}^{\varsigma} : W_b\left(\varsigma_b^*(\varepsilon)\right) \geq W_g(\bar{\varsigma})\}, \tag{42}$$

where $W_b(\varsigma)$ is given by (30). Such $\bar{\varepsilon}^{\varsigma}$ exists and is above $\underline{\varepsilon}^{\varsigma}$. Indeed, $W_g\left(\varsigma_g^*\left(\underline{\varepsilon}^{\varsigma}\right)\right) = W_g(\bar{\varsigma}) > W_b\left(\varsigma_b^*\left(\underline{\varepsilon}^{\varsigma}\right)\right)$.[27] Furthermore, $\lim_{\varepsilon \to \infty} W_g(\bar{\varsigma}) = -\infty$, and from (40) it follows that $\lim_{\varepsilon \to \infty} \hat{\gamma}_b\left(\varsigma_b^*(\varepsilon)\right) = 0$, which implies $\lim_{\varepsilon \to \infty} W_b\left(\varsigma_b^*(\varepsilon)\right) = \alpha_c > 0$.

By definition of $\bar{\varepsilon}^{\varsigma}$ (42), $W_g(\bar{\varsigma}) \geq W_b\left(\varsigma_b^*(\varepsilon)\right)$ for $\varepsilon \in (\underline{\varepsilon}^{\varsigma}, \bar{\varepsilon}^{\varsigma}]$. Therefore, for such values of ε, the regulator sets $\varsigma = \bar{\varsigma}$, and the green equilibrium is played. However, the externality is under-corrected relative to the green efficient allocation because $\bar{\varsigma} < \varsigma_g^*(\varepsilon)$.

Finally, we show that the regulator sets $\varsigma = \varsigma_b^*(\varepsilon)$ if $\varepsilon > \bar{\varepsilon}^{\varsigma}$. Note that the brown

[27] Here we assume that the green equilibrium is welfare-superior, which is the case if f is sufficiently small.

equilibrium exists under $\varsigma_b^*(\varepsilon)$ if $\varepsilon > \bar{\varepsilon}^{\varsigma}$ because $\varsigma_b^*(\varepsilon) > \varsigma_g^*(\varepsilon) > \bar{\varsigma}$. At the same time, the highest welfare achievable in the green equilibrium is $W_g(\bar{\varsigma})$. Therefore, it is sufficient to show that $W_b(\varsigma_b^*(\varepsilon)) > W_g(\bar{\varsigma})$ for $\varepsilon > \bar{\varepsilon}^{\varsigma}$. At $\varepsilon = \bar{\varepsilon}^{\varsigma}$, $\frac{d\left(W_g(\bar{\varsigma}) - W_b\left(\varsigma_b^*(\varepsilon)\right)\right)}{d\varepsilon}\Big|_{\varepsilon=\bar{\varepsilon}^{\varsigma}} \leq 0$ because otherwise $\bar{\varepsilon}^{\varsigma}$ is not an infimum. Using (30) and (41), we find that the derivative above is strictly negative for $\varepsilon > \bar{\varepsilon}^{\varsigma}$ because

$$\frac{d^2 W_g(\bar{\varsigma})}{d\varepsilon^2} = 0 \quad \text{and} \quad \frac{d^2 W_b(\varsigma_b^*(\varepsilon))}{d\varepsilon^2} = \frac{d\varsigma_b^*(\varepsilon)}{d\varepsilon} g\left(\hat{\gamma}_b\left(\varsigma_b^*(\varepsilon)\right)\right) \xi'\left(G\left(\hat{\gamma}_b\left(\varsigma_b^*(\varepsilon)\right)\right)\right) > 0,$$

where the latter inequality holds because $\varsigma_b^*(\varepsilon)$ is an increasing function (Lemma 5). Therefore, for $\varepsilon > \bar{\varepsilon}^{\varsigma}$, $W_g(\bar{\varsigma}) < W_b(\varsigma_b^*(\varepsilon))$, and the regulator sets $\varsigma = \varsigma_b^*(\varepsilon) > \varsigma_g^*(\varepsilon)$. Because $\varsigma_b^*(\varepsilon) > \varsigma_g^*(\varepsilon)$, the externality is over-corrected relative to the green efficient allocation. □

C.6 Adoption cost structure

In this appendix, we explore the importance of the adoption cost structure for our results. In Section C.6.1, we discuss why in the setting with the binary technology the pollution tax alone is generally not sufficient to implement the green efficient allocation. In Section C.6.2, we explore the model in which the adoption technology is continuous. We discuss the results in Section C.6.3.

C.6.1 Binary technology

In the green efficient allocation, the marginal investor's preference is given by (13). Adoption is welfare-improving if $W_g^{CP} > W_b^{CP}$, where W_b^{CP} and W_g^{CP} are given by (20) and (21), respectively. Simplifying, we get

$$\text{[Size CP]}: \ \hat{\gamma}_g^{CP} = \frac{\Delta - f}{\pi} - \varepsilon \xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right), \tag{43}$$

$$\text{[Adoption CP]}: \ f \leq \Delta\left(1 - \frac{G\left(\hat{\gamma}_b^{CP}\right)}{G\left(\hat{\gamma}_g^{CP}\right)}\right) + \frac{\varepsilon\xi\left(G\left(\hat{\gamma}_b^{CP}\right)\right) - \varepsilon\xi\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)}{G\left(\hat{\gamma}_g^{CP}\right)} + \tag{44}$$
$$\frac{\int_0^{\hat{\gamma}_b^{CP}} \gamma dG}{G\left(\hat{\gamma}_g^{CP}\right)} - \frac{\pi \int_0^{\hat{\gamma}_g^{CP}} \gamma dG(\gamma)}{G\left(\hat{\gamma}_g^{CP}\right)}.$$

Consider now the green equilibrium with tax, which we analyze in Section 4.3. We

have

$$[\text{Size Eq}]: \hat{\gamma}_g(\tau) = \frac{\Delta - f}{\pi} - \tau, \tag{45}$$

$$[\text{Adoption Eq}]: \frac{f}{1-\pi} \leq \frac{\int_0^{\hat{\gamma}_g(\tau)} \gamma dG(\gamma)}{G\left(\hat{\gamma}_g(\tau)\right)} + \tau. \tag{46}$$

Comparing the two sets of equations, (43)-(44) and (45)-(46), we can clearly see why the tax is generally not sufficient to implement the green efficient allocation. From (43) and (45), $\tau = \varepsilon\xi'\left(\pi G\left(\hat{\gamma}_g^{CP}\right)\right)$ corrects the externality conditional on the green technology adoption by making firm sizes equivalent in the green equilibrium and the green efficient allocation. However, the adoption decisions, given by (44) and (46), are not generally aligned at this tax level. Intuitively, this discrepancy arises because the planner compares investors' welfare *across equilibria*. In contrast, d-firms' managers take their shareholder base as given and do not internalize that non-adoption will lead to an equilibrium switch, which is associated with a non-infinitesimal change in firm size and shareholder composition.

C.6.2 Continuous convex technology

We now consider an economy equivalent to the baseline model except that d-firms can adjust their technology at the margin. Specifically, suppose now that d-firms can reduce their pollution intensity from 1 to $1-\iota$ by incurring a proportional convex cost $f(\iota)$, where ι is a continuous variable.[28] We assume that $f(0) = 0$ and $f(1)$ is sufficiently large, so that d-firms always pick $\iota \in [0, 1)$.

If investors expect that d-firms are going to pollute with intensity $1-\iota$, then investors with $\gamma \in [0, \hat{\gamma})$ become shareholders of d-firms, and investors with $\gamma \in [\hat{\gamma}, \bar{\gamma}]$ become shareholders of c-firms, where

$$\hat{\gamma} = \frac{\Delta - f(\iota)}{1-\iota} - \tau, \tag{47}$$

[28] When the adoption technology is continuous but non-convex, multiple equilibria are possible. The tax alone is then generally insufficient to implement the efficient allocation. For example, the binary adoption cost, considered in the baseline model, can be approximated by a continuous but non-convex technology.

where, as usual, τ is the pollution tax. This equation is analogous to (14) in the baseline model (with $\varsigma^f = 0$).

Managers of d-firms choose ι to maximize the utility of their average shareholder:

$$\max_{\iota} \left(\alpha_d - f(\iota)\right) G\left(\hat{\gamma}\right) - (1-\iota) G\left(\hat{\gamma}\right) \tau - (1-\iota) \int_0^{\hat{\gamma}} \gamma dG(\gamma).$$

The first-order condition is then

$$\frac{df}{d\iota} = \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G\left(\hat{\gamma}\right)} + \tau. \tag{48}$$

Equations (47)-(48) determine the size and the pollution intensity of d-firms.

Consider now the planner who chooses the amounts of capital invested in d- and c-firms, as well as the amount of resources spent on reducing pollution intensity. As in the baseline model, the planner follows the threshold rule and allocates polluting shares to investors with relatively weak green preferences. The planner's problem is

$$\max_{\hat{\gamma},\iota} \alpha_c + \left(\Delta - f\left(\iota\right)\right) G\left(\hat{\gamma}\right) - (1-\iota) \int_0^{\hat{\gamma}} \gamma dG\left(\gamma\right) - \varepsilon\xi\left((1-\iota) G\left(\hat{\gamma}\right)\right).$$

The planner's first-order conditions are

$$\hat{\gamma} = \frac{\Delta - f\left(\iota\right)}{1-\iota} - \varepsilon\xi'\left((1-\iota) G\left(\hat{\gamma}\right)\right), \tag{49}$$

$$\frac{df}{d\iota} = \frac{\int_0^{\hat{\gamma}} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}\right)} + \varepsilon\xi'\left((1-\iota) G\left(\hat{\gamma}\right)\right). \tag{50}$$

We immediately see that $\tau = \varepsilon\xi'\left(\left(1-\iota^{CP}\right) G\left(\hat{\gamma}^{CP}\right)\right)$, where ι^{CP} and $\hat{\gamma}^{CP}$ solve (49)-(50), makes (47)-(48) and (49)-(50) equivalent. Therefore, the tax fully corrects both firm size and adoption investments. Different from the binary technology case discussed in Section C.6.1, here both the planner's and the equilibrium first-order conditions are local, so the planner does not need to compare different regimes when deciding how much to spend on adoption. The only wedge between private and social incentives is the marginal pollution externality. By contrast, in Section C.6.1, the adoption wedge is nonlocal, as adoption entails a cross-equilibrium comparison.

C.6.3 Discussion

Our results suggest that the nature of technology adoption plays a central role in determining whether a linear pollution tax is sufficient to implement the efficient allocation. What is essential for such a tax to be insufficient is a degree of non-convexity in adoption costs, so that optimal technology choices are not always made at the margin. In this sense, our baseline model is better suited to capture large, discrete changes in production technologies or organizational practices, whereas convex cost functions more naturally describe fine-tuning of existing technologies. Importantly, the non-convex cost assumption is empirically plausible: many investments, including environmentally relevant ones, involve substantial fixed costs or organizational changes that make adoption lumpy (e.g., Doms and Dunne, 1998; Cooper, Haltiwanger, and Power, 1999; Fowlie, 2010; Ryan, 2012).

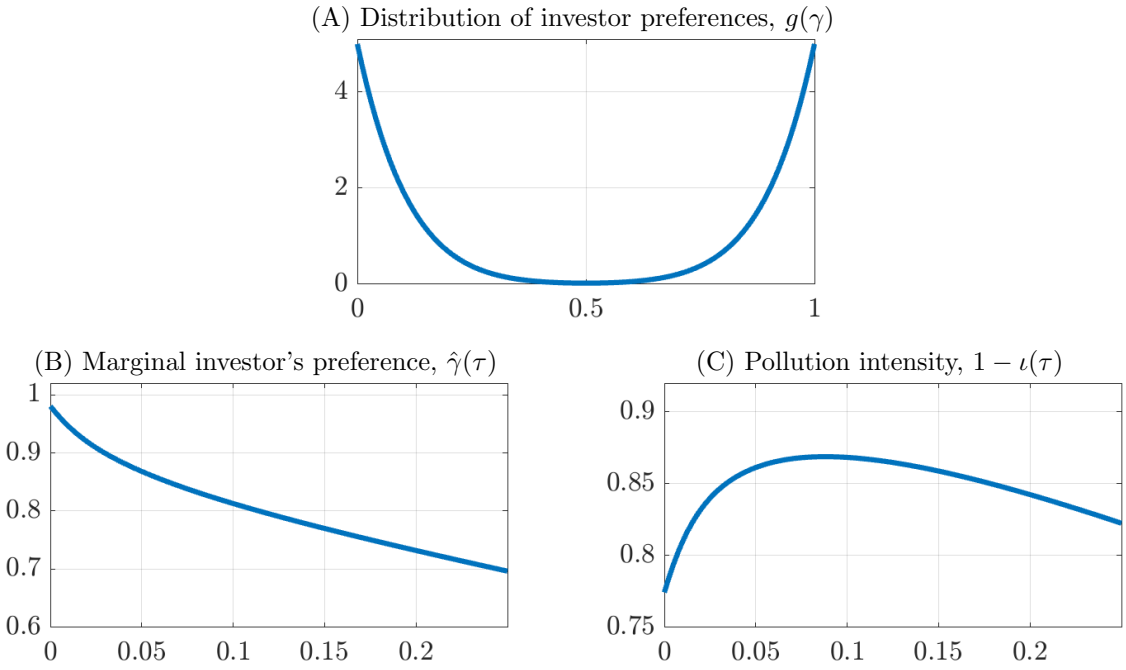


Figure 10: Panel (A): Probability density function of the distribution of investor preferences, $g(\gamma)$. Panel (B): Preference of a marginal investor as a function of pollution tax, $\hat{\gamma}(\tau)$. Panel (C): Pollution intensity as a function of pollution tax, $1-\iota(\tau)$. See Section C.6.2 for the model description. Parameterization: distribution of investor preferences is given by (19) with $w=0.5$, $a=10$, $\bar{\gamma}=1$; $\Delta=0.81$; $f(\iota)=\iota^2$.

A more general message of our paper is that the presence of investors with green preferences affects the efficacy of carbon policies. The conventional belief is that a higher

carbon tax diverts capital away from polluting firms and incentivizes them to adopt less polluting technologies. We emphasize that accounting for the shareholder-base effect casts doubt on this conventional wisdom. Specifically, a higher pollution tax can reduce d-firms' incentives to invest in green technology adoption, irrespective of the structure of the cost function. The underlying economic mechanism is a weakening of green preferences among d-firms' shareholders. If the shareholder-base effect is strong, the green equilibrium ceases to exist after an increase in the tax in our baseline model. Similarly, in the model of Section C.6.2, a higher τ can lead to an increase in pollution intensity $1-\iota$. We illustrate this with a numerical example in Figure 10.

C.7 Adoption as a timing option

In the baseline model, we assume that adoption costs are observable when investors make portfolio decisions and d-firms choose whether to adopt the green technology. In practice, the cost or efficacy of the green technology is frequently uncertain, and in this appendix we explore how this uncertainty interacts with the model's economic forces.

Specifically, as in the baseline model, we assume that d-firms can reduce pollution intensity of their assets from 1 to $\pi < 1$. Unlike in the baseline model, for a fraction $\lambda \in [0,1]$ of each d-firm's assets, reducing pollution intensity is costless (i.e., involves paying a proportional cost $f_L = 0$), while for the remaining $1-\lambda$ fraction it is expensive and involves paying a proportional cost $f_H > 0$.[29]

Firm managers and shareholders know λ and the cost parameters, but are initially unaware of which assets are easy to clean. They can wait until uncertainty is realized, or they can commit to adopt early, before uncertainty is realized. The advantage of early adoption is that it reduces the adoption cost f_H by $\varphi < f_H$.[30] However, committing to adopt early forgoes the option of waiting (e.g., due to irreversibility of early adoption investments) and greenifying only those assets for which it is costless to do so.

The timing of the model is summarized in Figure 11. At $t = 1$, before uncertainty

[29] Equivalently, one can assume that after shareholder bases are formed, a fraction λ of d-firms can adopt the green technology at zero cost, while the remaining fraction $1-\lambda$ faces an adoption cost f_H.

[30] Early commitment can reduce adoption costs through several channels, such as learning-by-doing or gradual integration of green technologies into the production process.

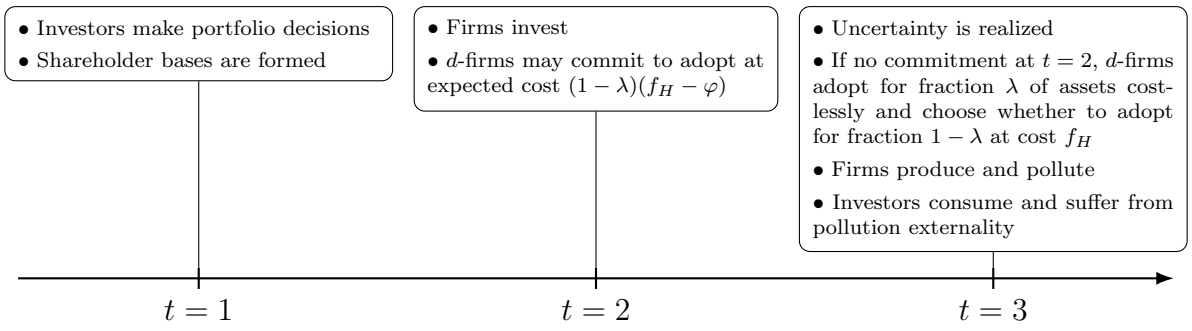


Figure 11: Timing of the model.

is realized, investors make portfolio decisions. At $t = 2$, d-firms invest and may commit to adopt early.[31] Capital cannot be reallocated after this stage. At $t = 3$, uncertainty is realized. If d-firms did not commit to adopt at $t = 2$, they adopt the green technology for easy-to-clean assets at zero cost and choose whether to adopt the green technology for hard-to-clean assets at cost f_H. To focus on an economically interesting case, we assume that f_H is sufficiently high so that if d-firms observe which assets are hard to clean, they never adopt the green technology for them. Namely, we assume that (see Equation (3) in the main text)

$$\frac{f_H}{1-\pi} > \int_0^{\bar{\gamma}} \gamma dG(\gamma). \tag{51}$$

This inequality implies that f_H is so high that an average investor in the entire population does not support the green technology adoption at this cost.

In what follows, we analyze the model. We first consider the cases with and without early commitment separately (Sections C.7.1 and C.7.2). We then characterize when d-firms choose to commit to adopt early (Section C.7.3). We discuss the welfare implications and analyze the effects of a pollution tax in Section C.7.4. Section C.7.5 concludes.

C.7.1 No early adoption

Suppose that d-firms choose to wait. As discussed above, at $t = 3$, d-firms adopt the green technology for easy-to-clean assets but do not adopt the green technology for

[31] We assume that d-firms adopt early if indifferent between doing so and waiting.

hard-to-clean assets, such that

$$\frac{\int_0^{\hat{\gamma}_l} \gamma dG(\gamma)}{G\left(\hat{\gamma}_l\right)} \geq 0 \quad \text{and} \quad \frac{\int_0^{\hat{\gamma}_l} \gamma dG(\gamma)}{G\left(\hat{\gamma}_l\right)} < \frac{f_H}{1-\pi}, \tag{52}$$

where $\hat{\gamma}_l$ is the threshold such that investors, expecting d-firms to forgo the option to adopt early, invest in d-firms if and only if $\gamma < \hat{\gamma}_l$. The threshold $\hat{\gamma}_l$ is determined by equating the expected values of investing one dollar in a c-firm and a d-firm, namely,

$$\alpha_c = \alpha_d - \hat{\gamma}_l \left(\pi\lambda + 1 - \lambda\right) \Leftrightarrow \hat{\gamma}_l = \frac{\Delta}{\pi\lambda + 1 - \lambda}. \tag{53}$$

Clearly, $\hat{\gamma}_l > 0$ because $\Delta > 0$. Furthermore, (52) holds if (51) holds.

In this case, output, pollution, and investors' welfare are, respectively,

$$\begin{aligned} &Y_l = \alpha_c \left(1 - G\left(\hat{\gamma}_l\right)\right) + \alpha_d G\left(\hat{\gamma}_l\right), P_l = \left(\pi\lambda + 1 - \lambda\right) G\left(\hat{\gamma}_l\right), \\ &W_l = Y_l - \left(\pi\lambda + 1 - \lambda\right) \int_0^{\hat{\gamma}_l} \gamma dG(\gamma) - \varepsilon\xi(P_l). \end{aligned}$$

C.7.2 Early adoption

Suppose now that d-firms commit to adopt early. This requires

$$\frac{\int_0^{\hat{\gamma}_e} \gamma dG(\gamma)}{G\left(\hat{\gamma}_e\right)} \geq \frac{\left(1-\lambda\right)\left(f_H - \varphi\right)}{1-\pi}, \tag{54}$$

where the threshold $\hat{\gamma}_e$ is determined by

$$\alpha_c = \alpha_d - \left(1-\lambda\right)\left(f_H - \varphi\right) - \hat{\gamma}_e \pi \Leftrightarrow \hat{\gamma}_e = \frac{\Delta - \left(1-\lambda\right)\left(f_H - \varphi\right)}{\pi}. \tag{55}$$

Clearly, $\hat{\gamma}_e > 0$ and (54) holds if the cost reduction due to early adoption φ is sufficiently large.

In this case, output, pollution, and investors' welfare are, respectively,

$$\begin{aligned} &Y_e = \alpha_c \left(1 - G\left(\hat{\gamma}_e\right)\right) + \left(\alpha_d - \left(1-\lambda\right)\left(f_H - \varphi\right)\right) G\left(\hat{\gamma}_e\right), P_e = \pi G\left(\hat{\gamma}_e\right), \\ &W_e = Y_e - \pi \int_0^{\hat{\gamma}_e} \gamma dG(\gamma) - \varepsilon\xi(P_e). \end{aligned}$$

C.7.3 Conditions for early-adoption and no-early-adoption equilibria

Suppose that investors expect d-firms not to adopt early. In this case, the threshold type is $\hat{\gamma}_l$, given by (53). For this to be an equilibrium, d-firms should be willing not to adopt early at $t = 2$, given their shareholder composition. That is,

$$(1-\lambda)\left(f_H-\varphi\right)G\left(\hat{\gamma}_l\right)+\pi\int_0^{\hat{\gamma}_l}\gamma dG(\gamma)>\left(\lambda\pi+1-\lambda\right)\int_0^{\hat{\gamma}_l}\gamma dG(\gamma),$$

where the left-hand side is the total cost (pecuniary and nonpecuniary) of adopting early, and the right-hand side is the total cost of waiting. Simplifying, we get

$$\frac{\int_0^{\hat{\gamma}_l}\gamma dG(\gamma)}{G\left(\hat{\gamma}_l\right)}<\frac{f_H-\varphi}{1-\pi}. \tag{56}$$

Suppose now that investors expect d-firms to adopt early. In this case, the threshold type is $\hat{\gamma}_e$, given by (55). For this to be an equilibrium, d-firms must be willing to adopt (i.e., (54) must hold), and early adoption must also be preferred to waiting. The latter is the case if

$$\frac{\int_0^{\hat{\gamma}_e}\gamma dG(\gamma)}{G\left(\hat{\gamma}_e\right)}\geq\frac{f_H-\varphi}{1-\pi}. \tag{57}$$

Note that (52) and (54) hold automatically if (56) and (57) hold. In particular, if d-firms have the option to wait, they have weaker incentives to adopt early. Indeed, in the absence of the waiting option, adoption occurs if the average shareholder prefers paying the average adoption cost $(1-\lambda)(f_H-\varphi)$, that is, if (54) holds. With the waiting option, early adoption becomes less attractive: it occurs only if the average shareholder prefers adopting the green technology for hard-to-clean assets at cost $f_H-\varphi$, that is, if (57) holds. Intuitively, the waiting option gives d-firms an opportunity to learn which assets are hard to clean. As a result, at $t = 2$, d-firms behave as if they know which assets are hard to clean. Knowing that at $t = 3$ they can still greenify easy-to-clean assets at zero cost, they choose to adopt early only if doing so is worthwhile for hard-to-clean assets. Importantly, they may still adopt early because it is cheaper to greenify hard-to-clean assets at $t = 2$ than at $t = 3$.

Lemma 9. *The option to wait and adopt at $t = 3$ reduces the size of the parameter region in which the early-adoption equilibrium exists.*

Proof. This result follows because the right-hand side of (57) is greater than the right-hand side of (54). □

The immediate implication of Lemma 9 is that the presence of the waiting option may eliminate the early-adoption equilibrium. Namely, even if such an equilibrium exists in the absence of the waiting option, it may cease to exist once d-firms have this option.

Even though the waiting option may eliminate the early-adoption equilibrium, multiple equilibria are still possible in this environment. Proposition 7 characterizes the conditions under which different equilibria arise.

Proposition 7. *There exist $f_H > \bar{\varphi} > \underline{\varphi} \geq 0$ such that*

(i) if $\varphi < \underline{\varphi}$, d-firms never adopt early;

(ii) if $\varphi \geq \bar{\varphi}$, d-firms always adopt early;

(iii) if $\varphi \in [\underline{\varphi}, \bar{\varphi})$, two equilibria coexist: in one, d-firms adopt early, in the other, d-firms do not adopt early.

Furthermore, if the two equilibria coexist, d-firms receive more funding in the early-adoption equilibrium, i.e., $\hat{\gamma}_e > \hat{\gamma}_l$, where $\hat{\gamma}_l$ and $\hat{\gamma}_e$ are given by (53) and (55), respectively.

Proof. See Appendix C.7.6. □

Proposition 7 is similar to Proposition 1 in the main text. Specifically, it shows that the early-adoption equilibrium exists if and only if the early-adoption cost reduction φ is sufficiently large. Conversely, when φ is small, the no-early-adoption equilibrium exists. Crucially, the two equilibria coexist for intermediate values of φ. In that case, if investors expect d-firms to commit to early adoption—and thus reduce pollution for all assets—then investors with relatively strong green preferences become d-firms' shareholders. This, in turn, justifies d-firms' willingness to adopt early and reduce the pollution intensity of all their assets. In contrast, if investors expect d-firms to forgo early adoption, they

anticipate that the hard-to-clean assets will remain highly polluting, and investors with moderate green preferences choose to invest in c-firms instead. This weakens ex-post support for early adoption.

Figure 12, analogous to Figure 1 in the main text, illustrates investor sorting when the two equilibria coexist. Panel (A) shows the values of investing in c- and d-firms as functions of the green preference parameter γ. If d-firms do not commit to early adoption, the marginal investor's preference is $\hat{\gamma}_l$, whereas it is $\hat{\gamma}_e$ if they commit. For the two equilibria to coexist, the resulting shareholder bases of d-firms must be consistent with investors' expectations. Specifically, the average d-firm shareholder must be willing to adopt early in the early-adoption equilibrium, $\psi(\hat{\gamma}_e) \geq \frac{f_H - \varphi}{1-\pi}$, and wait in the no-early-adoption equilibrium, $\psi(\hat{\gamma}_l) < \frac{f_H - \varphi}{1-\pi}$, where $\psi(\hat{\gamma}) = \frac{\int_0^{\hat{\gamma}} \gamma dG(\gamma)}{G(\hat{\gamma})}$. Panel (B), which depicts the average preference of d-firms' shareholder as a function of the marginal investor preference $\psi(\hat{\gamma})$, shows that this is indeed the case in this example: $\psi(\hat{\gamma}_e) > \frac{f_H - \varphi}{1-\pi} > \psi(\hat{\gamma}_l)$. Naturally, for the two equilibria to coexist, $\hat{\gamma}_e$ must exceed $\hat{\gamma}_l$. That is, investors with moderate green preferences, $\gamma \in [\hat{\gamma}_l, \hat{\gamma}_e)$, invest in d-firms only in the early-adoption equilibrium (Panel A), expecting those firms to adopt the green technology for all their assets. They bring additional capital to d-firms and make the shareholder base sufficiently pro-green for early adoption to occur.

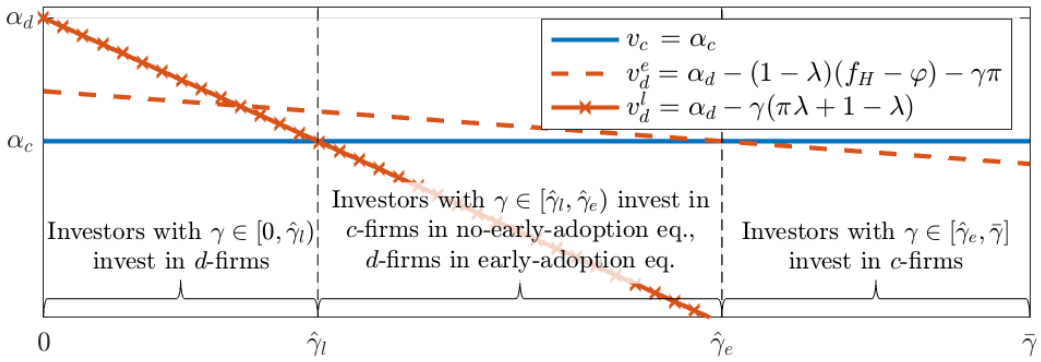
C.7.4 Welfare and pollution tax

As shown above, the model with a timing option is broadly similar to the model in the main text. Namely, the early-adoption equilibrium is analogous to the green equilibrium, as it features d-firms adopting the green technology for all their assets. The no-early-adoption equilibrium is analogous to the brown equilibrium because, in that equilibrium, d-firms do not adopt the green technology for hard-to-clean assets and therefore pollute more intensively.[32]

Importantly, since agents are atomistic, they do not internalize their effect on aggregate pollution, leaving room for policy intervention. While we do not provide the policy

[32] In line with our discussion in Section 3.2, we assume that the early-adoption equilibrium features lower pollution and that the socially preferred equilibrium is played if multiplicity is possible.

(A) Expected utility as a function of the nonpecuniary parameter γ



(B) Average green preference of d-firms' shareholders, $\psi(\hat{\gamma})$

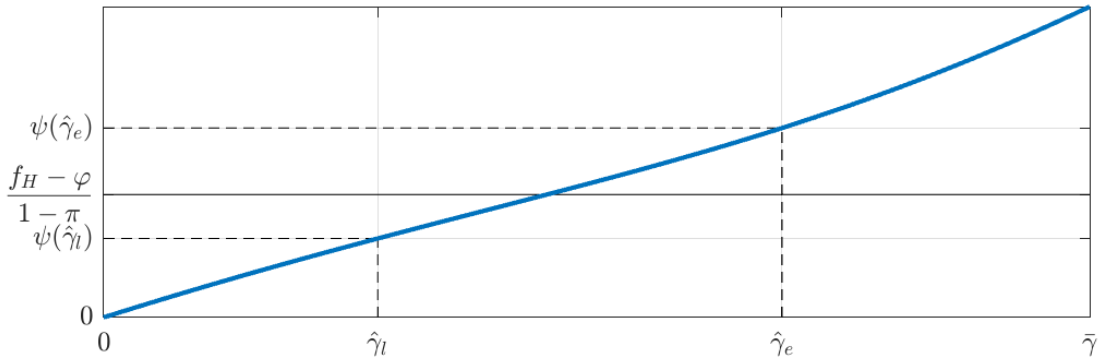


Figure 12: Panel (A): Values of investing one dollar in shares of c-firms (blue solid line, v_c), d-firms in early-adoption (red dashed line, v_d^e) and no-early-adoption equilibria (red line with cross markers, v_d^l) as functions of the green preferences strength γ. Panel (B): Average green preference of d-firms' shareholders, $\psi(\hat{\gamma}) = (G(\hat{\gamma}))^{-1} \int_0^{\hat{\gamma}} \gamma dG(\gamma)$ as a function of the marginal investor preference $\hat{\gamma}$ (blue solid line); marginal investors, $\hat{\gamma}_l$ and $\hat{\gamma}_e$; average green preferences of d-firms' shareholders, $\psi(\hat{\gamma}_l)$ and $\psi(\hat{\gamma}_e)$, in the no-early-adoption and early-adoption equilibria, respectively. Since $\psi(\hat{\gamma}_l) < \frac{f_H - \varphi}{1-\pi} < \psi(\hat{\gamma}_e)$, the two equilibria coexist.

analysis in the same detail as in the main text, it generally runs along the same lines. We do, however, show that the effects of a pollution tax are analogous to those in the main model. The following proposition is an analogue of Proposition 3 in the main text.

Proposition 8. *There exists* $\mathcal{S}_\tau^e = \bigcup_{i=1}^N (\underline{\tau}_i, \bar{\tau}_i)$, *where* $\frac{f_H - \varphi}{1-\pi} > \bar{\tau}_N > \underline{\tau}_N > \cdots > \underline{\tau}_1 \geq 0$, *such that the early-adoption equilibrium does not exist if and only if* $\tau \in \mathcal{S}_\tau^e$; *moreover,* $\mathcal{S}_\tau^e$ *is nonempty if* φ *is sufficiently close to* $\underline{\varphi}$, *and the shareholder-base effect dominates the direct effect of taxation,* $\frac{d\psi^\tau}{d\tau}\Big|_{\tau=0} < 0$.[33] *If the early-adoption equilibrium does not exist, the no-early-adoption equilibrium exists. Furthermore, in any equilibrium, an increase in* τ *leads to reductions in the amount of capital raised by d-firms, aggregate output, and*

[33] As in the main text, $\psi^\tau(\hat{\gamma})$ is given by (16).

pollution.

Proof. See Appendix C.7.6. □

Figure 13 illustrates Proposition 8. It is analogous to its main-text counterpart, Figure 3. In particular, it shows that increasing the tax beyond $\underline{\tau}_1$ eliminates the early-adoption equilibrium. As in the baseline model, the driving force is the shareholder-base effect. With the same preference distribution as in Example 1, a higher tax can make d-firms less willing to commit to early adoption.

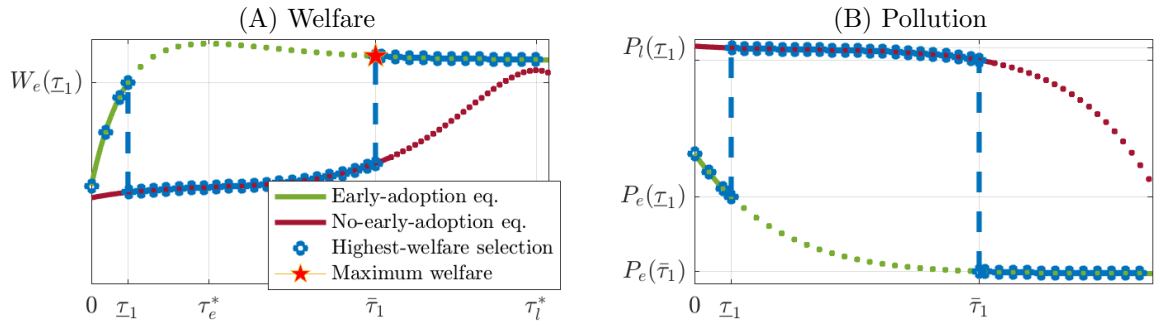


Figure 13: Welfare (panel A) and pollution (panel B) in the early-adoption equilibrium, the no-early-adoption equilibrium and under the highest-welfare selection criterion as functions of pollution tax τ. For early-adoption and no-early-adoption equilibria in both panels, solid/dotted lines show variables if a corresponding equilibrium exists/does not exist when adoption decisions are made based on shareholders' preferences. In panel (A), star marks welfare under the optimal tax. Parametrization: $\alpha_d = 1.6$, $\alpha_c = 1$, $\pi = 0.3$, $f_H = 0.5$, $\lambda = 0.2$, $\varphi = 0.1625$; distribution of γ: $\bar{\gamma} = 1.1$, $G(\gamma)$ is given by (19), with $w = 0.5$ and $a = 10$; the externality function is $\xi(x) = \frac{1}{4}x^4$, $\varepsilon = 25$.

C.7.5 Discussion

In this appendix, we interpret the green technology as a timing option. The key novel feature is that d-firms can either adopt the green technology early for all their assets at a discount, or wait and learn which assets are cheap to clean. Our analysis yields several new results.

First, the option to wait until uncertainty is resolved reduces d-firms' incentives to adopt early and may therefore eliminate the early-adoption equilibrium, whose absence is typically associated with higher aggregate pollution and lower social welfare.

Second, there exists a two-way feedback between the timing of option exercise and firms' shareholder base composition. Committing to early adoption attracts more pro-green investors to d-firms, since these investors anticipate that d-firms will adopt the

green technology for all assets, including those that are relatively expensive to clean. The presence of such investors, in turn, justifies early adoption of the green technology for all assets despite the relatively high cost. In contrast, if investors expect d-firms to forgo early adoption, the resulting shareholder base of d-firms has, on average, weaker green preferences, which in turn justifies the unwillingness to incur the costs needed to greenify hard-to-clean assets.

Third, a pollution tax can delay option exercise and increase pollution. A pollution tax reduces d-firms' size, but it can also make early adoption infeasible through the shareholder-base effect. As in the baseline model, the tax reallocates the most pro-green shareholders away from d-firms and toward c-firms, thereby weakening d-firms' incentives to commit to costly—but socially beneficial—early adoption.

Of course, our analysis explores the timing-option channel only at a high level. Future work could examine in greater detail how the gradual release of information shapes shareholder composition through trading, and how these dynamics interact with firms' decisions regarding the timing and scale of green-technology investment.

C.7.6 Proofs

Proposition 7

Proof. Suppose that investors expect d-firms not to adopt early. In this case, the threshold type is $\hat{\gamma}_l$, given by (53). For this to be an equilibrium, d-firms should be willing not to adopt early, that is,

$$(1-\lambda)\left(f_H-\varphi\right)G\left(\hat{\gamma}_l\right)+\pi\int_0^{\hat{\gamma}_l}\gamma dG(\gamma)>\left(\lambda\pi+1-\lambda\right)\int_0^{\hat{\gamma}_l}\gamma dG(\gamma),$$

where the left-hand side is the total cost (pecuniary and nonpecuniary) of adopting early, and the right-hand side is the total cost of waiting. Simplifying, we get

$$\varphi<\bar{\varphi}\equiv(1-\pi)\left(\frac{f_H}{1-\pi}-\frac{\int_0^{\hat{\gamma}_l}\gamma dG(\gamma)}{G\left(\hat{\gamma}_l\right)}\right), \tag{58}$$

where the right-hand side is positive because we assume that f_H is sufficiently high such that (52) always holds. Obviously, $\bar{\varphi}<f_H$.

Suppose now that investors expect d-firms to adopt early. In this case, the threshold type is $\hat{\gamma}_e$, given by (55). For this to be an equilibrium, d-firms should be willing to adopt early, that is, (54) must hold and

$$(1-\lambda)(f_H-\varphi)G(\hat{\gamma}_e)+\pi\int_0^{\hat{\gamma}_e}\gamma dG(\gamma)\leq(\lambda\pi+1-\lambda)\int_0^{\hat{\gamma}_e}\gamma dG(\gamma)\Leftrightarrow\varphi\geq\underline{\varphi}, \quad (59)$$

where $\underline{\varphi}$ is implicitly defined as a solution of

$$\underline{\varphi}=(1-\pi)\left(\frac{f_H}{1-\pi}-\frac{\int_0^{\hat{\gamma}_e(\underline{\varphi})}\gamma dG(\gamma)}{G\left(\hat{\gamma}_e\left(\underline{\varphi}\right)\right)}\right). \quad (60)$$

This equation has a unique solution because the right-hand side decreases in $\hat{\gamma}_e$, which in turn increases in φ by (55). We again have $\underline{\varphi}\in(0,f_H)$.[34]

Furthermore, for this to be an equilibrium, (54) must hold. Since the right-hand side of (54) decreases in φ, while the left-hand side of (54) increases in φ because $\hat{\gamma}_e$ increases in φ, we know that (54) holds for all $\varphi\geq\underline{\varphi}$ if it holds for $\varphi=\underline{\varphi}$. It is immediate to see that (54) is satisfied at $\varphi=\underline{\varphi}$.

We now show that $\underline{\varphi}<\bar{\varphi}$. To verify that, notice that

$$\hat{\gamma}_e(\varphi)\geq\hat{\gamma}_l\Leftrightarrow\varphi\geq\check{\varphi}\equiv f_H-\Delta\frac{1-\pi}{\pi\lambda+1-\lambda}.$$

Clearly, $\check{\varphi}<\bar{\varphi}$. Indeed, plugging $\check{\varphi}$ into (58), we see that

$$\check{\varphi}<\bar{\varphi}\Leftrightarrow\frac{\Delta}{\pi\lambda+1-\lambda}>\frac{\int_0^{\hat{\gamma}_l}\gamma dG(\gamma)}{G(\hat{\gamma}_l)},$$

which is true because the left-hand side of the last inequality is simply $\hat{\gamma}_l$, while the right-hand side is expected γ conditional on $\gamma\leq\hat{\gamma}_l$. Next, we use the definition of $\bar{\varphi}$ to write

$$\bar{\varphi}=(1-\pi)\left(\frac{f_H}{1-\pi}-\frac{\int_0^{\hat{\gamma}_l}\gamma dG(\gamma)}{G(\hat{\gamma}_l)}\right)\overset{\hat{\gamma}_e(\bar{\varphi})>\hat{\gamma}_l}{>}(1-\pi)\left(\frac{f_H}{1-\pi}-\frac{\int_0^{\hat{\gamma}_e(\bar{\varphi})}\gamma dG(\gamma)}{G(\hat{\gamma}_e(\bar{\varphi}))}\right),$$

where we used the fact that $\hat{\gamma}_e(\varphi)>\hat{\gamma}_l$ for $\varphi=\bar{\varphi}>\check{\varphi}$. Therefore, at $\varphi=\bar{\varphi}$ the

[34] We have $\underline{\varphi}>0$ if (51) holds. At the same time, $\underline{\varphi}<f_H$ because, at $\varphi=f_H$, we have $\hat{\gamma}_e(f_H)=\frac{\Delta}{\pi}>0$, such that the left-hand side of (60) is greater than the right-hand side of (60).

early-adoption equilibrium exists, which implies $\bar{\varphi} > \underline{\varphi}$.

Overall, we have shown that the early-adoption equilibrium exists if $\varphi \geq \underline{\varphi}$ and the no-early-adoption equilibrium exists if $\varphi < \bar{\varphi}$. Furthermore, $\bar{\varphi} > \underline{\varphi}$. Finally, if $\varphi \in [\underline{\varphi}, \bar{\varphi})$, then $\hat{\gamma}_e(\varphi) > \hat{\gamma}_l$. Suppose not, then from (58), we have

$$\varphi < \bar{\varphi} \Leftrightarrow \varphi < (1-\pi)\left(\frac{f_H}{1-\pi} - \frac{\int_0^{\hat{\gamma}_l} \gamma dG(\gamma)}{G\left(\hat{\gamma}_l\right)}\right) \leq (1-\pi)\left(\frac{f_H}{1-\pi} - \frac{\int_0^{\hat{\gamma}_e(\varphi)} \gamma dG(\gamma)}{G\left(\hat{\gamma}_e\left(\varphi\right)\right)}\right),$$

which, from (59), implies that the early-adoption equilibrium does not exist, contradicting the result that this equilibrium exists if $\varphi \geq \underline{\varphi}$. □

Proposition 8

Proof. We start by proving that the early-adoption equilibrium exists for a sufficiently large and small values of τ. By Proposition 7, the early-adoption equilibrium exists if $\varphi \geq \underline{\varphi}$ and $\tau = 0$, i.e.,

$$\psi^{\tau}\left(\hat{\gamma}_e(0), 0\right) = \frac{\int_0^{\hat{\gamma}_e(0)} \gamma dG(\gamma)}{G\left(\hat{\gamma}_e(0)\right)} \geq \frac{f_H - \varphi}{1-\pi},$$

where $\psi^{\tau}(\hat{\gamma}, \tau)$ is defined in (16), i.e.,

$$\psi^{\tau}\left(\hat{\gamma}, \tau\right) = \frac{\int_0^{\hat{\gamma}} \gamma dG\left(\gamma\right)}{G\left(\hat{\gamma}\right)} + \tau,$$

and

$$\hat{\gamma}_e\left(\tau\right) = \frac{\Delta - (1-\lambda)\left(f_H - \varphi\right)}{\pi} - \tau. \tag{61}$$

Because $\psi^{\tau}\left(\hat{\gamma}_e(\tau), \tau\right)$ is a continuous function of τ, it then follows that there exists $\underline{\tau} \geq 0$ such that $\psi^{\tau}\left(\hat{\gamma}_e(\tau), \tau\right) \geq \frac{f_H - \varphi}{1-\pi}$ on $\tau \in [0, \underline{\tau}]$.

Next, by Proposition 7, at $\tau = 0$ and $\varphi \geq \underline{\varphi}$, $\hat{\gamma}_e > \hat{\gamma}_l$, which is equivalent to $\Delta > \left(\frac{\pi\lambda + 1 - \lambda}{1-\pi}\right)\left(f_H - \varphi\right)$. Therefore, at $\tau = \frac{f_H - \varphi}{1-\pi}$, we have

$$\hat{\gamma}_e\left(\frac{f_H - \varphi}{1-\pi}\right) = \frac{1}{\pi}\left(\Delta - \left(\frac{\pi\lambda + 1 - \lambda}{1-\pi}\right)\left(f_H - \varphi\right)\right) > 0.$$

Consequently, if $\tau \in \left[\frac{f_H - \varphi}{1-\pi}, \frac{\Delta - (1-\lambda)(f_H - \varphi)}{\pi}\right)$, the early-adoption equilibrium exists. This

is because d-firms raise nonzero capital, $\hat{\gamma}_e(\tau) > 0$, and d-firms commit to adopt early, i.e., $\psi^\tau\left(\hat{\gamma}_e(\tau), \tau\right) > \frac{f_H - \varphi}{1-\pi}$. Furthermore, by continuity, there exists a $\bar{\tau} < \frac{f_H - \varphi}{1-\pi}$ such that the early-adoption equilibrium exists on $\tau \in \left[\bar{\tau}, \frac{\Delta - (1-\lambda)(f_H - \varphi)}{\pi}\right)$.

We proceed to show that the early-adoption equilibrium might not exist for some intermediate range of τ. The early-adoption equilibrium does not exist if $\psi^\tau\left(\hat{\gamma}_e\left(\tau\right), \tau\right) < \frac{f_H - \varphi}{1-\pi}$. Define set $\mathcal{S}_\tau^e = \left\{\tau : \psi^\tau\left(\hat{\gamma}_e\left(\tau\right), \tau\right) < \frac{f_H - \varphi}{1-\pi}\right\}$. Since $\psi^\tau\left(\hat{\gamma}_e\left(\tau\right), \tau\right)$ is a smooth function of τ, $\mathcal{S}_\tau^e$ is a countable union of disjoint open intervals, i.e., $\mathcal{S}_\tau^e = \bigcup_{i=1}^N (\underline{\tau}_i, \bar{\tau}_i)$, where $\frac{f_H - \varphi}{1-\pi} > \bar{\tau}_N > \underline{\tau}_N > \cdots > \underline{\tau}_1 \geq \underline{\tau}$, such that the early-adoption equilibrium does not exist if and only if $\tau \in \mathcal{S}_\tau^e$. To show that this set is generally nonempty, suppose that $\varphi = \underline{\varphi}$. Then, by definition of $\underline{\varphi}$, $\psi^\tau\left(\hat{\gamma}_e(0, \underline{\varphi}), 0\right) = \frac{f_H - \underline{\varphi}}{1-\pi}$, where we write $\hat{\gamma}_e$ as a function of τ and φ, i.e., $\hat{\gamma}_e = \hat{\gamma}_e(\tau, \varphi)$. If $\frac{d\psi^\tau}{d\tau}\big|_{\tau=0} < 0$, then a marginal increase in τ from 0 implies that the early-adoption equilibrium ceases to exist. Then the set $\mathcal{S}_\tau^e$ takes the form as conjectured in the proposition because $\psi^\tau\left(\hat{\gamma}_e(\tau, \varphi), \tau\right)$ is a smooth function of τ and φ.

We now show that the no-early-adoption equilibrium exists if the early-adoption equilibrium does not. The threshold in the no-early-adoption equilibrium is

$$\hat{\gamma}_l(\tau) = \frac{\Delta}{\pi\lambda + 1 - \lambda} - \tau,$$

and its analogue in the early-adoption equilibrium, $\hat{\gamma}_e(\tau)$, is given by (61). Note that by Proposition 7, $\hat{\gamma}_e(\tau) > \hat{\gamma}_l(\tau)$ because $\varphi \geq \underline{\varphi}$.[35] Therefore, if the early-adoption equilibrium does not exist, i.e., $\psi^\tau(\hat{\gamma}_e(\tau), \tau) < \frac{f_H - \varphi}{1-\pi}$, then the no-early-adoption equilibrium exists because $\psi^\tau(\hat{\gamma}, \tau)$ is an increasing function of $\hat{\gamma}$ and so $\psi^\tau(\hat{\gamma}_l(\tau), \tau) < \psi^\tau(\hat{\gamma}_e(\tau), \tau) < \frac{f_H - \varphi}{1-\pi}$.

We are left to conduct the comparative statics of capital raised by d-firms, output, and pollution with respect to τ. Capital raised by d-firms in the early-adoption equilibrium is $K_{d,e} = G\left(\hat{\gamma}_e\left(\tau\right)\right) \Rightarrow \frac{dK_{d,e}}{d\tau} = -g\left(\hat{\gamma}_e\left(\tau\right)\right) < 0$, and in the no-early-adoption equilibrium is $K_{d,l} = G\left(\hat{\gamma}_l\left(\tau\right)\right) \Rightarrow \frac{dK_{d,l}}{d\tau} = -g\left(\hat{\gamma}_l\left(\tau\right)\right) < 0$. The negative impact of τ on capital raised by d-firms implies that pollution in both equilibria declines in τ because $P_e = \pi K_{d,e}$ and $P_l = (\pi\lambda + 1 - \lambda)K_{d,l}$. Output in both equilibria also declines in τ

[35] Proposition 7 shows that if $\varphi > \underline{\varphi}$, then $\hat{\gamma}_e(0) > \hat{\gamma}_l(0)$. Under taxation, the ranking of the thresholds preserves because the difference $\hat{\gamma}_e(\tau) - \hat{\gamma}_l(\tau)$ does not depend on τ.

because $Y_e = \alpha_c + K_{d,e}\left(\Delta - (1-\lambda)(f_H - \varphi)\right)$ and $Y_l = \alpha_c + K_{d,l}\Delta$. Note that if the early-adoption equilibrium exists, it must be that $\hat{\gamma}_e > 0 \Rightarrow \Delta > (1-\lambda)(f_H - \varphi)$. □

C.8 Investors' hedging motives

In the baseline model, we assume that investors are risk-neutral. As a result, shareholder composition features full separation: investors with above-threshold green preferences invest only in c-firms, while investors with below-threshold green preferences invest only in d-firms. In reality, investors may have hedging motives, making this separation less stark. In this appendix, we show that some of our key results are robust along this dimension.

C.8.1 Setting

The setup remains very similar to the main text, so we present it briefly and focus on the new features introduced in this appendix.

Firms Each c-firm raises capital k_c from investors and produces the final good using a linear technology, $y_c = (\alpha_c + \epsilon_c)k_c$, where $\epsilon_c \sim N(0, \sigma^2)$ is a common shock to all c-firms. Each d-firm raises capital k_d and produces the final good using a linear technology, $y_d = k_d\left(\alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}} + \epsilon_d\right)$, where $\epsilon_d \sim N(0, \sigma^2)$ is a common shock to all d-firms.[36] To keep the analysis concise, we assume that ϵ_c and ϵ_d are uncorrelated. In addition, firms face a pollution tax τ.

Investors To keep the analysis tractable, we assume that investors have mean-variance objectives, such that the portfolio problem of an investor γ is

$$\max_{\{w_i^\gamma\}} \sum_{i\in\{c,d\}} w_i^\gamma v_i - \frac{1}{2}\eta\sigma^2 \sum_{i\in\{c,d\}} (w_i^\gamma)^2 - \varepsilon\xi(P), \tag{62}$$
$$\text{s.t.} \sum_{i\in\{c,d\}} w_i^\gamma = 1, \text{ and } w_i^\gamma \geq 0 \;\forall i,$$

[36] One can also introduce purely idiosyncratic shocks, but these can be diversified away by holding a portfolio of firms of the same type.

where η is the risk-aversion parameter, w_c^γ and w_d^γ denote the amounts of wealth invested in c- and d-firms, and v_c and v_d are the per-dollar values of investing in c- and d-firms, given by[37]

$$v_c = \alpha_c \quad \text{and} \quad v_d(\gamma) = \alpha_d - f\mathbb{1}_{\{\mathsf{a}_d=1\}} - (\gamma+\tau)\left(\pi + (1-\pi)\mathbb{1}_{\{\mathsf{a}_d=0\}}\right).$$

The second term in (62) is new and does not appear in the baseline model. Naturally, in the risk-neutral case, $\eta = 0$, this term disappears, and the problem simplifies to (2).

The following lemma characterizes portfolio allocation of risk-averse investors.

Lemma 10. *There exist thresholds $\hat{\gamma}_H > \hat{\gamma}_L$,*

$$\hat{\gamma}_H = \frac{\Delta - f\mathbb{1}_{\{\mathsf{a}_d=1\}} + \eta\sigma^2}{\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}} - \tau \quad \textit{and} \quad \hat{\gamma}_L = \frac{\Delta - f\mathbb{1}_{\{\mathsf{a}_d=1\}} - \eta\sigma^2}{\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}} - \tau, \tag{63}$$

such that investors with $\gamma > \hat{\gamma}_H$ (if any) invest all their wealth in c-firms, $w_c^\gamma = 1$ and $w_d^\gamma = 0$, and investors with $\gamma < \hat{\gamma}_L$ (if any) invest all their wealth in d-firms, $w_c^\gamma = 0$ and $w_d^\gamma = 1$. Investors with $\gamma \in [\hat{\gamma}_L, \hat{\gamma}_H]$ invest in firms of both types,

$$w_c^\gamma = \frac{\gamma - \hat{\gamma}_L}{\hat{\gamma}_H - \hat{\gamma}_L} \quad \textit{and} \quad w_d^\gamma = 1 - w_c^\gamma. \tag{64}$$

Moreover, for investors with $\gamma \in [\hat{\gamma}_L, \hat{\gamma}_H]$, w_c^γ increases in γ, and w_d^γ decreases in γ.

Proof. See Appendix C.8.3. □

Lemma 10 generalizes Lemma 1 from the main text. Investors with sufficiently strong green preferences, $\gamma > \hat{\gamma}_H$, still invest only in c-firms: they dislike holding polluting shares so much that they avoid d-firms altogether, even though doing so forgoes the diversification benefit. In contrast, investors with sufficiently weak green preferences, $\gamma < \hat{\gamma}_L$, invest only in d-firms. For these investors, the expected financial loss from investing in c-firms outweighs the diversification benefit.

Importantly, investors with moderate green preferences, $\gamma \in [\hat{\gamma}_L, \hat{\gamma}_H]$, invest in both c- and d-firms. For these investors, green preferences are neither strong enough to justify

[37] Problem (62) is the analogue of (2), where we recast the optimization problem in terms of $w_i^\gamma = s_i^\gamma p_i$, using the fact that $p_i = k_i$. As in the main text, we assume that investors cannot borrow and that bonds are in zero net supply, such that there is no savings in equilibrium, implying $w_c^\gamma + w_d^\gamma = 1$.

fully avoiding d-firms nor weak enough to justify fully avoiding c-firms. As a result, they do not want to hold fully polarized portfolios and instead prefer to reap the diversification benefit by holding both types of firms. Even so, they tilt their portfolios according to their green preferences: the amount of wealth invested in c-firms, w_c^γ, is increasing in γ.

Quite naturally, the mass of investors who invest in both firm types increases with risk aversion: from (63), $\hat{\gamma}_H$ increases in η and $\hat{\gamma}_L$ decreases in η. In particular, when $\eta = 0$, we are back to the baseline model: $\hat{\gamma}_H = \hat{\gamma}_L$, so the mass of such investors is zero. In contrast, if η is sufficiently high—so that $\hat{\gamma}_H > \bar{\gamma}$ and $\hat{\gamma}_L < 0$—then all investors invest in both firm types.

In what follows, we assume that η is not too high, such that $0 < \hat{\gamma}_L < \hat{\gamma}_H < \bar{\gamma}$ in both equilibria.

Green technology adoption decision At $t = 2$, after investors have chosen their portfolios and shareholder bases have been formed, managers of d-firms choose whether to adopt the green technology. The payoff uncertainty is unaffected by the adoption decisions, and so a d-firm adopts the green technology if and only if

$$\psi^\tau \equiv \frac{\int_0^{\bar{\gamma}} \gamma w_d^\gamma dG(\gamma)}{\int_0^{\bar{\gamma}} w_d^\gamma dG(\gamma)} + \tau \geq \frac{f}{1-\pi}. \tag{65}$$

This inequality is an analogue of (16) in the main text. The only difference is that d-firms' shareholders now contribute different amounts of capital, so managers of d-firms weight investors' preferences according to their capital contributions.

C.8.2 Equilibrium characterization

As in the main text, two symmetric equilibria are possible. In the brown equilibrium, d-firms do not adopt the green technology, and in the green equilibrium, d-firms adopt the green technology. From Lemma 10, we have

$$\hat{\gamma}_H^b = \Delta + \eta\sigma^2 - \tau \quad \text{and} \quad \hat{\gamma}_L^b = \Delta - \eta\sigma^2 - \tau, \tag{66}$$

and

$$\hat{\gamma}_H^g = \frac{\Delta - f + \eta\sigma^2}{\pi} - \tau \quad \text{and} \quad \hat{\gamma}_L^g = \frac{\Delta - f - \eta\sigma^2}{\pi} - \tau. \tag{67}$$

The brown equilibrium exists if (65) fails under (66), while the green equilibrium exists if (65) holds under (67). As in the baseline model (Proposition 1), a higher Δ makes the green equilibrium more likely and the brown equilibrium less likely; that is, $\frac{d\psi^\tau}{d\Delta} \geq 0$, where ψ^τ is defined in (65).

More importantly, the effect of the pollution tax remains qualitatively similar. On the one hand, a higher tax directly incentivizes adoption, $\frac{\partial \psi^\tau}{\partial \tau} > 0$. On the other hand, the shareholder-base effect operates in the opposite direction.

Lemma 11. *An increase in Δ increases the willingness to adopt the green technology ψ^τ. An increase in τ increases the willingness to adopt through the direct effect but reduces it through the shareholder-base effect.*

Proof. See Appendix C.8.3. □

C.8.3 Proofs

Lemma 10

Proof. The Lagrangian to the problem (62) can be written as

$$\begin{aligned}\mathcal{L} =& w_c^\gamma \alpha_c + (1 - w_c^\gamma)\left(\alpha_d - f\mathbb{1}_{\{\mathsf{a_d}=1\}} - (\gamma + \tau)\left(\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a_d}=0\}}\right)\right) - \\ & \frac{\eta\sigma^2}{2}\left[(w_c^\gamma)^2 + (1 - w_c^\gamma)^2\right] + \underline{\nu}^\gamma w_c^\gamma + \bar{\nu}^\gamma (1 - w_c^\gamma),\end{aligned}$$

where $\underline{\nu}^\gamma \geq 0$ and $\bar{\nu}^\gamma \geq 0$ are the Lagrange multipliers on the constrains $w_c^\gamma \geq 0$ and $1 - w_c^\gamma \geq 0$, respectively. Differentiating with respect to w_c^γ immediately yields that the $1 - w_c^\gamma \geq 0$ constraint binds, such that $\bar{\nu}^\gamma > 0$, if and only if

$$\gamma > \hat{\gamma}_H \equiv \frac{\Delta - f\mathbb{1}_{\{\mathsf{a}_d=1\}} + \eta\sigma^2}{\pi + (1-\pi)\,\mathbb{1}_{\{\mathsf{a}_d=0\}}} - \tau,$$

and the $w_c^\gamma \geq 0$ constraint binds, such that $\underline{\nu}^\gamma \geq 0$, if and only if

$$\gamma < \hat{\gamma}_L \equiv \frac{\Delta - f\mathbb{1}_{\{\mathtt{a}_d=1\}} - \eta\sigma^2}{\pi + (1-\pi)\,\mathbb{1}_{\{\mathtt{a}_d=0\}}} - \tau.$$

If $\gamma \in [\hat{\gamma}_L, \hat{\gamma}_H]$, we have $\bar{\nu}^\gamma = \underline{\nu}^\gamma = 0$, and the straightforward differentiation yields that optimal w_c^γ is given by (64). □

Proof of Lemma 11

Proof. The willingness to adopt $\psi^\tau(\Delta, \tau)$ is given by

$$\psi^\tau(\Delta,\tau) = \frac{\int_0^{\hat{\gamma}_L} \gamma dG(\gamma) + \int_{\hat{\gamma}_L}^{\hat{\gamma}_H} \gamma w_d^\gamma(\gamma)\, dG(\gamma)}{G(\hat{\gamma}_L) + \int_{\hat{\gamma}_L}^{\hat{\gamma}_H} w_d^\gamma(\gamma)\, dG(\gamma)} + \tau,$$

where $\hat{\gamma}_L(\Delta,\tau)$ and $\hat{\gamma}_H(\Delta,\tau)$ are given by (63), and $w_d^\gamma(\Delta,\tau)$ is given by (64). Differentiating with respect to Δ, we get

$$\frac{d\psi^\tau}{d\Delta} = \frac{1}{2\eta\sigma^2} \times T,$$

where

$$T = \frac{\int_{\hat{\gamma}_L}^{\hat{\gamma}_H} dG(\gamma)}{G(\hat{\gamma}_L) + \int_{\hat{\gamma}_L}^{\hat{\gamma}_H} w_d^\gamma(\gamma)\, dG(\gamma)} \left\{ \frac{\int_{\hat{\gamma}_L}^{\hat{\gamma}_H} \gamma dG(\gamma)}{\int_{\hat{\gamma}_L}^{\hat{\gamma}_H} dG(\gamma)} - \frac{\int_0^{\hat{\gamma}_L} \gamma dG(\gamma) + \int_{\hat{\gamma}_L}^{\hat{\gamma}_H} \gamma w_d^\gamma(\gamma)\, dG(\gamma)}{G(\hat{\gamma}_L) + \int_{\hat{\gamma}_L}^{\hat{\gamma}_H} w_d^\gamma(\gamma)\, dG(\gamma)} \right\}.$$

We have $T > 0$ because the first term in the curly parentheses is the average γ conditional on $\gamma \in [\hat{\gamma}_L, \hat{\gamma}_H]$, while the second term is the average γ, weighted by a weakly decreasing $w_d^\gamma(\gamma)$, conditional on $\gamma \in [0, \hat{\gamma}_H]$.

Next, differentiating $\psi^\tau(\Delta,\tau)$ with respect to τ, we get

$$\frac{d\psi^\tau}{d\tau} = 1 - \frac{1}{\hat{\gamma}_H - \hat{\gamma}_L} T,$$

where the second term represents the shareholder-base effect. □