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# Adoption of green technology with financial friction☆

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ABSTRACT

We investigate firms' incentives to adopt green technology. To cover the adoption costs, a firm needs a bank loan. The bank cannot observe firms' adoption costs and offers a loan contract that allows it to earn an intermediation margin. The Pigouvian tax leads to optimal abatement but inefficiently low adoption. The first-best outcome is achieved via a combination of environmental tax and loan subsidy. If the regulator is restricted to an environmental tax, it faces a trade-off between optimal adoption and optimal abatement. In this case, the second-best tax rate exceeds the Pigouvian tax rate.

## 1. Introduction

Many countries agreed to ambitious reduction goals regarding greenhouse gas emissions; see the Paris Agreement (Nations, 2015), the European Green Deal (Commission, 2020). To achieve these goals, tremendous investments in green transformation are needed. The actual financial flows into the green transformation fall short of the financial flows needed to achieve long-term climate and sustainability goals – i.e., there is a vast *climate finance gap* (Hong et al., 2020; Yilmaz et al., 2023; Kapeller et al., 2023).[1]

Closing the gap requires huge investments by private companies and households. For instance, steel companies need to adopt their production plants to produce steel with green or blue hydrogen instead of fossil fuels, and private households need to switch from oil and gas heating to heat pumps. To cover these massive adoption and investment costs, most companies and households need outside finance, e.g., bank loans. That financial constraints reduce green investments is well-documented in the literature (Zhang and Vigne, 2021; Accetturo et al., 2022; De Haas et al., 2024; Ng et al., 2023; Costa et al., 2024; Qin et al., 2024; Martinsson et al., 2024).[2]

We investigate the interplay between financial constraints and environmental policy in a model where firms can decide to adopt a new carbon-friendly technology. Firms differ in their adoption costs and are financially constrained. A firm needs to obtain a bank loan to adopt green technology. The bank earns an intermediation margin, and thus, the number of firms who receive a loan that allows them to cover their adoption costs is too low – a form of *credit crunch* arises. Without financial constraints, the Pigouvian tax – that equals the marginal externality – leads to optimal abatement and adoption (Requate and Unold, 2001). With financial frictions, the Pigouvian tax leads to an adoption rate that is too low from a welfare perspective. In this case, a combination of Pigouvian tax and loan subsidy can achieve the first-best outcome. If the regulator is restricted to an environmental tax only, it faces a trade-off

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[1] The importance of finance for combating climate change is addressed by special issues on 'climate and sustainable finance'; e.g., by Review of Financial Studies (Hong et al., 2020), Journal of International Financial Management & Accounting (Verdoliva and Vigne, 2022), and Finance Research Letters (Cardillo et al., 2024).

[2] Financial constraints lead to more dirty production (Andersen, 2017) and more greenwashing (Zhang, 2022).

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between optimal adoption and abatement. The second-best optimal tax rate exceeds the Pigouvian tax rate. The paper analyzes the two most essential policy mechanisms for moving corporations to reduce their carbon footprints – taxes and subsidies – according to a recent survey by Stroebel and Wurgler (2021) among finance academics, professionals, and regulators. It is the first theoretical study of firms that can respond to rising carbon prices by increasing abatement or adopting green technology, the latter requiring a loan from the house bank.

The paper contributes to two strands of literature[3]: (i) the adoption of green technologies and (ii) the interplay of environmental regulations and financial frictions. The incentives environmental policies create to adopt green technology are analyzed by Requate and Unold (2001). They show that if the regulator commits to an aggregate emissions level, taxes lead to over-adoption, while cap-and-trade leads to under-adoption. If the regulator knows the new technology, she can achieve optimal adoption with both regulations irrespective of whether she moves before or after adoption. The case of a monopolistic upstream firm that engages in R&D and sells advanced technology to polluting firms is studied by Denicolò (1999) and Requate (2005). Denicolò (1999) shows that if the regulator commits to a policy, taxes provide stronger R&D incentives than tradable permits. Comparing various policy timings, Requate (2005) shows that ex-ante commitment to a menu of tax rates outperforms commitment to a single tax rate, interim commitment, and ex-post regulation. Instead of analyzing a monopolistic manufacturer who distorts the quality of its products, we investigate the distortion caused by a monopolistic bank that earns an intermediation margin.[4]

A recent and growing literature investigates the interplay between environmental policies and financial frictions. Hoffmann et al. (2017) assume a moral hazard problem between financially constrained firms and investors. The optimal (nonlinear) marginal tax is lower than the marginal externality as a more stringent environmental policy increases the deadweight loss caused by outside finance. Inderst and Heider (2023) analyze an industry with green and brown firms. They model an agency problem regarding external finance à la Holmstrom and Tirole (1997), which leads to a restricted maximal investment of firms. They show that the optimal policy is stricter than the Pigouvian level if the industry, in aggregate, is not financially constrained. A moral hazard problem regarding external finance is also analyzed by Döttling and Rola-Janicka (2023), who allow for climate-related transition and physical risk. The optimal tax rate is below the marginal externality if there is no physical risk. In the case of transition and physical risk, the optimal tax rate can be higher or lower than the marginal externality. Haas and Kempa (2023) model financial friction as an adverse selection problem. In their model, skilled and unskilled firms differ in the probability of successfully inventing a green technology. Due to credit rationing, the Pigouvian tax alone may lead to underinvestment. An interest rate subsidy or loan guarantee can solve the issue of credit rationing. For some parameter constellations, a tax larger than the marginal externality resolves the credit rationing and implements the first-best outcome. This finding relies on the assumption that emission reduction is achieved only via the invention of new technology but not via abatement, i.e., for a given technology, emissions are fixed. As Haas and Kempa (2023), we investigate financial frictions caused by a monopolistic bank with imperfect information regarding loan applicants' benefits from a financial contract. In our model, emissions for a given technology are endogenous, and thus, an environmental tax that exceeds the marginal externality distorts firms' abatement decisions. Nevertheless, we show that such a high environmental tax is the second-best optimal.

## 2. The model

We consider an industry with a continuum of independent firms of measure one over two periods, $t = 0, 1$. The market interest rate is $r \geq 0$. At $t = 0$, each firm owns a preexisting brown technology, $T = B$. At $t = 0$, a firm can decide whether or not to adopt a new green technology, $T = G$. The abatement cost function of technology $T \in \{B, G\}$ is

$$c_T(q^{BAU} - q), \tag{1}$$

where $q^{BAU} > 0$ denote the business-as-usual emissions and $q \in [0, q^{BAU}]$ are the actual emissions.

**Assumption 1.**

(i) $c'_B(\Delta) > c'_G(\Delta) > 0$ for all $\Delta > 0$;

(ii) For $T \in \{B, G\}$: $c''_T(\Delta) > 0$ for all $\Delta \geq 0$;

(iii) $c'_B(0) = c'_G(0) = 0$ and $\lim_{\Delta \to q^{BAU}} c'_T(\Delta) = +\infty$ for $T \in \{B, G\}$.

For each technology, the abatement cost function is increasing and convex, Assumption 1(i) and (ii). Initial pollution reductions can often be achieved at low costs, while further reductions require expensive changes in operating procedures (Phaneuf and Requate, 2016; Kuik et al., 2009). To ensure interior solutions, we impose Inada conditions, Assumption 1(iii).

A firm that switches from the preexisting brown technology to the new green technology incurs an adoption cost of $\theta$ at $t = 0$. The adoption costs $\theta \in [\underline{\theta}, \bar{\theta}]$, with $0 < \underline{\theta} < \bar{\theta}$, are distributed according to density $f(\theta) > 0$ and c.d.f. $F(\theta)$ in the industry. The adoption cost is private information of the respective firm.

**Assumption 2.** The virtual type

$$\psi(\theta) \equiv \theta + \frac{F(\theta)}{f(\theta)} \tag{2}$$

is strictly increasing in $\theta$.

[3] The paper contributes to the literature on directed technological change and the transition towards clean technology (Aghion et al., 2016; Acemoglu et al., 2016).

[4] The diffusion of green technology as a reaction to the regulation of standards is analyzed by Wang et al. (2021).

Assumption 2 is standard in mechanism design and often referred to as the 'regular case' (Laffont and Martimort, 2009; Börgers, 2015). It is satisfied by most single-peaked densities (Bagnoli and Bergstrom, 1989).

Production takes place in $t = 1$, which implies that a firm incurs the abatement costs in $t = 1$. Each firm owns an initial wealth of $\pi_0$ and generates a $\pi_1 > 0$ revenue at $t = 1$. We assume that $\pi_1$ is sufficiently large so that a firm can cover its total expenses at $t = 1$.

The production causes environmental damage at period $t = 1$. The marginal environmental damage is $\rho > 0$. The regulator can impose a per-unit environmental tax $\tau \geq 0$.

A firm's initial wealth might not cover the adoption costs at $t = 0$. A monopolistic bank offers loan contracts, which allow firms to cover the adoption costs and repay the loan with cost savings at $t = 1$.

The timing of the game is as follows.

$t = 0$ (i) The regulator determines the market regulations.
(ii) The bank offers loan contracts to the firms.
(iii) Each firm decides whether or not to adopt technology $T = G$ (and whether to accept the loan offer).

$t = 1$ (i) Each firm decides on its emissions $q_T$, depending on the chosen technology $T \in \{B, G\}$.
(ii) Each firm generates revenue $\pi_1$, pays the environmental taxes, and repays its debt in case of a loan contract.

*Welfare optimal allocation.* The welfare optimal allocation $(q_B^*, q_G^*, \hat{\theta}^*)$ specifies the amount of emissions $q_T^*$ for each technology $T \in \{B, G\}$ and an adoption cost threshold $\hat{\theta}^*$. Note that the abatement cost of a firm depends on the available technology but not on the type $\theta$. Adopting green technology is welfare optimal for a firm if its adoption cost is sufficiently low, i.e., below $\hat{\theta}^*$. The aggregated discounted social costs – the sum of abatement and adoption costs and the environmental damage – are

$$SC(q_B, q_G, \hat{\theta}) = \int_{\underline{\theta}}^{\hat{\theta}} \left\{ \frac{1}{1+r} \left[ c_G(q^{BAU} - q_G) + \rho q_G \right] + \theta \right\} f(\theta)\, \mathrm{d}\theta + \int_{\hat{\theta}}^{\bar{\theta}} \frac{1}{1+r} \left[ c_B(q^{BAU} - q_B) + \rho q_B \right] f(\theta)\, \mathrm{d}\theta. \tag{3}$$

The first-order conditions are

$$c_T'(q^{BAU} - q_T^*) = \rho \quad \text{for } T \in \{B, G\} \tag{4}$$

$$\hat{\theta}^* = \frac{1}{1+r} \left[ c_B(q^{BAU} - q_B^*) - c_G(q^{BAU} - q_G^*) + \rho(q_B^* - q_G^*) \right] \tag{5}$$

Condition (4) states that in optimum, the marginal costs of abatement are equal to the marginal damage. This implies that $q_B^* > q_G^*$. Condition (5) requires that the optimal marginal type is equal to the discounted total cost savings (abatement plus environmental costs) from switching from technology $B$ to $G$. We assume that the boundaries of the type distribution are such that $\underline{\theta} < \hat{\theta}^* < \bar{\theta}$.[5]

## 3. Individual optimization without financial friction

First, we consider the case without financial friction. Suppose that $\pi_0 \geq \bar{\theta}$ so that each firm can afford to switch to green technology.

At $t = 1$ a firm that operates with technology $T \in \{B, G\}$ minimizes $c_T(q^{BAU} - q) + \tau q$, which is independent of $\theta$. The optimal emissions levels $\hat{q}_T(\tau)$ are characterized by the first-order conditions

$$c_T'(q^{BAU} - \hat{q}_T(\tau)) = \tau. \tag{6}$$

A higher tax leads to lower emissions, $d\hat{q}_T/d\tau < 0$, as empirically documented by Brown et al. (2022) and Martinsson et al. (2024). For any tax rate $\tau \geq 0$, $\hat{q}_B(\tau) > \hat{q}_G(\tau)$. Let

$$K_T(\tau) = c_T(q^{BAU} - \hat{q}_T(\tau)) + \tau \hat{q}_T(\tau) \tag{7}$$

be the total costs of a firm that uses technology $T$ at $t = 1$. Note that $K_T'(\tau) = \hat{q}_T(\tau) > 0$. A firm with adoption cost $\theta$ switches to green technology at $t = 0$ if and only if

$$\theta \leq \frac{1}{1+r} \left[ K_B(\tau) - K_G(\tau) \right] \equiv \hat{\theta}(\tau). \tag{8}$$

The higher the emissions tax, the higher the incentives to adopt the green technology, $\hat{\theta}'(\tau) > 0$.

The regulator sets the emissions tax to minimize the discounted social costs

$$SC(\tau) = \int_{\underline{\theta}}^{\hat{\theta}(\tau)} \left\{ \frac{1}{1+r} \left[ c_G(q^{BAU} - \hat{q}_G(\theta)) + \rho \hat{q}_G(\theta) \right] + \theta \right\} f(\theta)\, \mathrm{d}\theta + \int_{\hat{\theta}(\tau)}^{\bar{\theta}} \frac{1}{1+r} \left[ c_B(q^{BAU} - \hat{q}_B(\tau)) + \rho \hat{q}_B(\tau) \right] f(\theta)\, \mathrm{d}\theta. \tag{9}$$

**Proposition 1.** *Without financial friction, the Pigouvian tax $\tau^* = \rho$ induces both (i) optimal abatement ($\hat{q}_T(\rho) = q_T^*$ for $T \in \{B, G\}$) and (ii) optimal adoption ($\hat{\theta}(\rho) = \hat{\theta}^*$); i.e., the Pigouvian tax induces the first-best outcome.*

[5] These results are known in the literature (Requate and Unold, 2001).

**Proof.** All proofs are displaced to the Supplementary material. □

The finding that one instrument is sufficient to achieve both goals in the case without friction is also shown by Requate and Unold (2001).

## 4. Financial friction

We assume that $\pi_0 = 0$ and that firms do not have access to a perfect financial market. If a firm wants to invest in green technology at $t = 0$, it needs a loan from the monopolistic bank.

The adoption cost is the private information of a firm. The bank offers a menu of loan contracts – a direct revelation mechanism – $\{p(\theta), L(\theta), R(\theta)\}$. Here, $p(\theta) \in [0, 1]$ denotes the probability that the firm obtains a loan. The loan amount obtained at $t = 0$ is $L(\theta) \geq \theta$, and the firm has to repay $R(\theta)$ at $t = 1$. One interpretation is that the applicant firm discusses its needs with a bank clerk, thereby indirectly disclosing its adoption costs. The bank clerk then decides whether or not to offer a loan agreement consisting of a loan amount and an interest rate. The bank maximizes its expected profit

$$\Pi = \int_{\underline{\theta}}^{\bar{\theta}} p(\theta) \left[ \frac{1}{1+r} R(\theta) - L(\theta) \right] f(\theta) \, \mathrm{d}\theta. \tag{10}$$

A firm of type $\theta$ that participates in the loan scheme and reports truthfully makes an expected discounted profit of

$$U(\theta) = \frac{1}{1+r}\pi_1 + p(\theta) \left\{ L(\theta) - \theta - \frac{1}{1+r}[K_G(\tau) + R(\theta)] \right\} - [1 - p(\theta)] \frac{1}{1+r} K_B(\tau). \tag{11}$$

The firm obtains revenue $\pi_1$ at $t = 1$. In the case of a bank loan, it obtains $L(\theta)$ and pays the adoption cost $\theta$ at $t = 0$. In period $t = 1$, the firm repays the loan, $R(\theta)$, and incurs abatement and tax costs of size $K_G(\tau)$. If the firm does not obtain a loan, it incurs abatement and tax costs of size $K_B(\tau)$ at $t = 1$.

If a firm does not participate in the loan scheme, its profit is

$$U_0 = \frac{1}{1+r}[\pi_1 - K_B(\tau)]. \tag{12}$$

The advantage of a firm of type $\theta$ from taking part in the loan scheme is $M(\theta) = U(\theta) - U_0$, where

$$M(\theta) = p(\theta) \left\{ L(\theta) - \theta + \frac{1}{1+r}[K_B(\tau) - K_G(\tau) - R(\theta)] \right\}. \tag{13}$$

Thus, the bank solves

$$\max_{\{p(\theta), M(\theta)\}_{\theta \in [\underline{\theta}, \bar{\theta}]}} \int_{\underline{\theta}}^{\bar{\theta}} \left\{ -M(\theta) + p(\theta) \left[ \frac{1}{1+r}(K_B(\tau) - K_G(\tau)) - \theta \right] \right\} f(\theta) \, \mathrm{d}\theta \tag{14}$$

subject to: for all $\theta \in [\underline{\theta}, \bar{\theta}]$

$$M'(\theta) = p(\theta) \tag{IC}$$

$$M(\theta) \geq 0 \tag{PC}$$

The bank maximizes its expected profit subject to firms' participation constraints (PC) and the (local) incentive compatibility constraint (IC).

**Lemma 1.** *The profit-maximizing loan scheme specifies*

$$p^{SB}(\theta) = \begin{cases} 1 & \text{if } \psi(\theta) \leq \frac{1}{1+r}[K_B(\tau) - K_G(\tau)] \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

*There exists a critical type $\hat{\theta}^{SB}(\tau)$, implicitly defined by*

$$\psi(\hat{\theta}^{SB}(\tau)) \equiv \frac{1}{1+r}[K_B(\tau) - K_G(\tau)], \tag{16}$$

*so that only types $\theta \leq \hat{\theta}^{SB}(\tau)$ adopt the green technology.*

Note that all types $\theta \leq \hat{\theta}^{SB}(\tau)$ obtain the same loan contract.[6] This is the well-known "no-haggling result" from Riley and Zeckhauser (1983). One optimal (indirect) loan contract, consisting of a fixed loan amount and a repayment (principal plus interest payment), is:

$$L^{SB} = \hat{\theta}^{SB} \quad \text{and} \quad R^{SB} = K_B(\tau) - K_G(\tau).$$

In the first-best case, all types with adoption costs that do not exceed the discounted cost savings from the technology switch adopt technology $G$. With financial friction, only those whose virtual adoption costs do not exceed the discounted cost savings adopt technology $G$.

[6] Strictly speaking, $\hat{\theta}^{SB}(\tau)$ is defined by (16) only if it is interior.

**Proposition 2.** *With financial friction, the Pigouvian tax, $\tau^* = \rho$, leads to too little adoption of green technology; i.e., $\hat{\theta}^{SB}(\rho) < \hat{\theta}^*$.*

The Pigouvian tax induces optimal abatement but not optimal adoption.

*Environmental tax and loan subsidy.* Suppose the regulator can set next to the environmental tax $\tau$ a loan subsidy $S$. Any firm that obtains a loan and adopts technology $G$ receives this amount for free. Thus, the loan subsidy boosts demand for bank loans. An alternative interpretation is that the bank receives the amount of $S$ for any loan granted.

With environmental tax and loan subsidy, all firms with adoption cost $\theta \leq \hat{\theta}^{SB}(\tau, S)$ obtain a bank credit (with $p(\theta) = 1$), where $\theta \leq \hat{\theta}^{SB}(\tau, S)$ is implicitly defined by

$$\psi(\hat{\theta}^{SB}(\tau, S)) \equiv \frac{1}{1+r}[K_B(\tau) - K_G(\tau)] + S. \tag{17}$$

**Proposition 3.** *With financial friction, the Pigouvian tax, $\tau^* = \rho$, in combination with the optimal loan subsidy, $S^* = F(\hat{\theta}^*)/f(\hat{\theta}^*)$, implements the first-best outcome (optimal abatement and optimal adoption).*

In the case of financial friction, the two instruments – environmental tax and loan subsidy – are sufficient to implement the first-best outcome. A similar result is obtained by Haas and Kempa (2023), who analyze a situation where firms differ in their probabilities of successfully inventing a new clean technology. Three instruments are needed to implement the first-best outcome if the friction is caused by a monopolistic inventor and owner of the new green technology who licenses the technology to the firms (Phaneuf and Requate, 2016). The reason is that an optimal adoption subsidy leads to excessive R&D efforts.

Proposition 3 crucially relies on two assumptions. First, the government is not financially constrained, and public funds have no shadow costs. Second, the market friction is caused by a pure financial intermediary and not by a monopolistic firm that engages in R&D itself or can distort the quality of the new technology downwards to screen the adopting firms more effectively.

Surprisingly, the more firms in the industry have relatively low adoption costs, the higher the optimal loan subsidy. The following corollary shows this for linear density functions.

**Corollary 1.** *Let $\theta$ be distributed according to c.d.f. $F(\theta|a) = (1+a)\theta - a\theta^2$ on $[0,1]$ with $a \in [-1,1]$. Then, the optimal subsidy*

$$S^* = \frac{(1+a)\hat{\theta}^* - a(\hat{\theta}^*)^2}{1 + a - 2a\hat{\theta}^*} \tag{18}$$

*is increasing in $a$; i.e., the more firms have low adoption costs, the higher the optimal subsidy.*

*Environmental tax only.* If the loan subsidy is costly for the regulator, a high loan subsidy is not the second-best optimal. In the following, we consider that the regulator can set only an environmental tax $\tau$.

A higher environmental tax not only increases abatement but also enhances the adoption of green technology, i.e.,

$$\frac{d\hat{\theta}^{SB}}{d\tau} = \frac{\hat{q}_B(\theta) - \hat{q}_G(\theta)}{(1+r)\psi'(\hat{\theta}^{SB})} > 0. \tag{19}$$

That higher environmental taxes increase green R&D investments and thereby reduce emissions is empirically documented by Brown et al. (2022) and Finkelstein Shapiro and Metcalf (2023).

When minimizing the social costs, the regulator faces a trade-off between optimal abatement and adoption.

**Proposition 4.** *The second-best optimal environmental tax*

$$\tau^{SB} = \rho + \frac{F(\hat{\theta}^{SB})[\hat{q}_B - \hat{q}_G]}{\psi'(\hat{\theta}^{SB})[-F(\hat{\theta}^{SB})\frac{d\hat{q}_G}{d\tau} - (1 - F(\hat{\theta}^{SB}))\frac{d\hat{q}_B}{d\tau}] + \frac{1}{1+r}f(\hat{\theta}^{SB})[\hat{q}_B - \hat{q}_G]^2} \tag{20}$$

*exceeds the Pigouvian tax, $\tau^{SB} > \rho = \tau^*$.*

Eq. (20) implicitly defines the second-best optimal tax rate. The numerator and the denominator of (20) are strictly positive. A more stringent environmental policy than the Pigouvian level is optimal if there is financial friction and the regulator is restricted to a tax-only policy. The second-best tax rate leads to too high abatement levels but shifts the adoption rate closer to the efficient level.

## 5. Conclusion

We analyzed the incentives of financially constrained firms to adopt green technology. The results apply not only to private companies but also to private households. Like firms, private households react in their decisions to adopt green technology mainly to financial incentives (Jacksohn et al., 2019). For private households, access to credit provided by the house bank is often crucial for adopting green technology. The results apply to advanced economies with a well-developed banking system and here rather to bank-oriented economies.[7]

[7] Fiorillo et al. (2022) show that financial markets in bank-oriented and market-oriented financial systems have a different influence on green innovations.

Ideally, the regulator uses a combination of environmental tax and a subsidy on green credits to enhance green technology adoption. Regulators are financially constrained, and public funds have shadow costs. In this case, the (second-best) optimal environmental tax exceeds the (marginal) externality. With actual $CO_2$ prices often being below the marginal social cost of carbon (Tol, 2023), this paper favors an increase in these prices. This insight is partly shared by Inderst and Heider (2023), Döttling and Rola-Janicka (2023), and Haas and Kempa (2023) but in contrast to Hoffmann et al. (2017). High environmental taxes are sometimes difficult to push through politically, as there is an aversion to such taxes (Andreassen et al., 2024). The consideration of such political constraints is an interesting area for future research.

## Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.frl.2024.106388.

## Data availability

No data was used for the research described in the article.

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