ENVIRONMENTAL POLICY WITH FINANCIAL FRICTIONS*

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Abstract

We examine the relationship between financial constraints and environmental policy using the Holmström and Tirole (1997) workhorse model, incorporating emission externalities and industry equilibrium. Our findings reveal that financial constraints do not consistently necessitate a more lenient emissions cap or lower emissions pricing. Instead, stricter policies than Pigouvian benchmarks may be optimal when firms' financial resources are not heavily constrained, as production reduction and increased product prices create a positive pecuniary externality for less polluting firms. Furthermore, under financial constraints, initial allocation of emissions rights is no longer welfare neutral.

Keywords: Financial constraints; environmental policy; emission trading rights.

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1 Introduction

Across the globe, governments step up their efforts to combat climate change.[1] As a consequence, many industries will have to undergo radical changes to become greener and ultimately decarbonized. Imposing emission prices on firms that truly reflect their social costs is a major instrument in this endeavour. For instance, the High-Level Commission on Carbon Prices, led by Joseph Stiglitz and Nicholas Stern, concluded that a range of 40–80 US $ per ton of CO2 in 2020, rising to 50–100 US $ per ton of CO2 by 2030, would be needed to achieve the objective of the Paris Agreement (Stern and Stiglitz 2017, 2021). This contrasts sharply with the fact that in 2021 less than 5 % of the USA's more than 36 billion tons of industrial and energy related CO2 emissions were explicitly priced, indicating the enormous financial burden that is yet to come.[2] Firms will have both to invest in abatement activities and to adopt more sustainable technologies. These immense financing needs are increasingly recognized by policy (cf. the Glasgow Pact of September 2021 on "Adaptation Financing") as well as by private investors demanding a carbon premium (Bolton and Kacperczyk 2021a, 2021b).

Such a considerable need for new investment and capital should not come without frictions. These frictions may arise from informational asymmetries between firm insiders and outside investors or from dilution of insiders' stakes and with this a misalignment of incentives, as has been recognized by a large literature in notably corporate finance and macrofinance.[3] They also impose limits on the amount of external financing that a

[1] In Europe, the Commission has committed itself to such transformation under the so-called "Green Deal". See also the Glasgow summit's Climate Pact https://unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf

[2] While a fuel excise is levied on the road sector, also this falls short of the required price of carbon (https://www.oecd.org/tax/tax-policy/carbon-pricing-united-states.pdf). In Europe, emission prices under the cap-and-trade mechanism were constantly below 10 € per ton in all the years leading up to 2018, though in 2022 they have reached unprecedented heights of up to 100 € per ton.

[3] In corporate finance, Jensen and Meckling (1976) and Myers and Majluf (1984) represent the seminal contributions on such an agency theory of financial frictions. From a macroeconomic perspective, the seminal reference is Bernanke and Gertler (1989), who build on the costly state verification model of Townsend (1979).

single firm or an entire industry can raise. Recent evidence suggests more specifically that firms' financial constraints indeed affect corporate environmental policies, reducing their abatement activities and increasing emissions (Xu and Kim 2022, Bartram et al. 2022). In our model, public environmental policy affects firm environmental policy both directly and indirectly through a higher financial burden.

Such a perspective on the green transformation seems to have been largely overlooked so far - not only in the public debate, but also in scholarly work. Instead, the implications and optimality of different environmental instruments, such as emission taxes or cap-and-trade regimes, are derived without consideration of potential frictions associated with the required investment and external financing.[4] This observation defines the objective of our research: We set out to examine the interaction between financing frictions, emission externalities, and environmental policy. For this we employ the by now standard workhorse model of Holmström and Tirole (1997). There, firms' financing capacity is endogenously limited by the availability of internal funds. To derive welfare implications, we model not only investment decisions but also supply and demand on the product market. All firms are price takers, which allows us to abstract from well-known frictions due to market power. A cap-and-trade scheme makes emissions costly, generating incentives for abatement activities and also determining the relative advantage of low- vs. high-polluting firms. In equilibrium, firms in different industries invest in production, abatement activities, and in the purchase of emission rights, which trade at a uniform market-clearing price. For instance, the EU Emissions Trading System (EU ETS) imposes such a cap on CO2 emissions across various industries.[5]

Without financing constraints, only firms with the least-polluting technologies should

[4] Corporate finance models in turn do not incorporate externalities and the costs they impose on firms, through taxes, costly emission rights, or necessary abatement activities.

[5] While there is no global CO2 cap in place in the US, as already mentioned above, allowance trading systems apply to SO2 and NOx under the Acid Rain Programme (https://www.epa.gov/acidrain/acid-rain-program). The SO2 allowance-trading programme, established under the 1990 Clean Air Act Amendments, was the world's first large-scale pollutant cap-and-trade system.

be active, and a Pigiouvian emission trading price, equalling marginal social costs of the respective pollutant, would optimally govern the size of the sector as well as abatement activities. With financial frictions, investment capacity of all firms, including the least-polluting ones, is limited. At first somewhat counterintuitively, this can make it optimal to reduce the total cap on emissions and thereby increase the price of emissions beyond the Pigouvian benchmark. By reducing aggregate output, this pushes up the product price, which for the least-polluting firms more than compensates for the higher price of emissions, ultimately relaxing their financial constraints and thus increasing their share of total output. For more polluting firms, instead, the higher price of emissions dominates, reducing their output. The optimality of such a prima facie excessively restrictive environmental policy thus hinges crucially on firm-level financial constraints, notably for low-polluting firms.

We note that in our model, less polluting firms are not disadvantaged in their access to external finance. Such a disadvantage would, however, reinforce the isolated effect, and there exists evidence confirming such a disadvantage.[6] Instead, without financial constraints at the firm level, the Pigouvian level for the price of emission rights would optimally allocate market shares across high- and low-polluting firms. Our finding of an optimally stricter environmental policy also speaks to the, in environmental economics, famous "Porter hypothesis", which hypothesizes that rather than losing out under stricter environmental regulation, firm profits may increase. In our setting, it is low-polluting firms that benefit and that increase investment and production not only in relative but also in absolute terms.[7]

[6] With individual loan data, Kempa et al. (2021) document differences between the costs of debt of non-renewable energy firms and and those using renewable technologies. Also Noailly and Smeets (2015) document more severe financing constraints for renewable energy firms. Across industries, Cecere et al. (2020) document financial constraints for eco-innovators (and a corresponding benefit of public financing). We note, however, that the evidence on bond prices for more or less renewable firms is mixed (e.g., Fammer 2020 or Larcker and Watts 2020).

[7] See Porter and Linde (1995), who suggest a dynamic mechanism of spurring innovation (see also Lambertini 2017 for a formalization).

The optimality of a stricter environmental policy and with it a higher price of emission rights contrasts with the insights from the literature on directed technological change, following Acemoglu et al. (2012), as there a lower price of emissions is optimal, accompanied by direct subsidies. We note that we do not consider subsidies targeted at individual firms or technologies.[8] An additional tool that we consider, however, is the initial allocation of permission rights, which can serve to alleviate financial constraints, particularly for low-polluting firms. While a system of "grandfathering", whereby typically rights are allocated according to past pollution, would be counterproductive, allocating emission rights even uniformly across firms can improve efficiency, even if this leads to windfall profits also for more-polluting firms. The latter will however optimally trade these rights, instead of increasing their output. More generally, whether and how emission rights are initially allocated is no longer welfare-neutral under financial constraints.

Some of our predictions and normative implications change when financial constraints are particularly severe, so that they constrain not only individual firms but also aggregate investment. Such severe financing constraints at the industry level would result when firms' internal funds are particularly low and governance problems particularly high, both of which may be more likely in new industries and in industries with less tangible assets. When these are less prone to emissions, our main guidance would still be to make environmental policy more rather than less stringent, albeit such differences between industries would generally call for a more sector-specific approach. This could also be achieved through a sector-specific allocation of emission rights, alleviating financial constraints rather than "grandfathering" existing pollution, which would not sacrifice other benefits of operating a single cap-and-trade scheme. We also note, however, that in economies with less developed capital markets and weak legal institutions, severe financial constraints may render particularly important the realization of higher output and consumer welfare,

[8] Some recent contributions have introduced financial constraints into such a model of directed technological change, though without isolating the pecuniary externality via the product market that is key to our analysis (Campiglio et al. 2022 and Pan et al. 2021).

so that environmental policy should optimally be more lenient.

To the best of our knowledge, the literature on environmental and resource economics has not addressed the issue that is at the core of our analysis, that is frictions in raising capital and firms' financing constraints. Capital market imperfections have however been recognized more generally as obstacles to a green transition (e.g., Stern and Stiglitz 2021). Such frictions are at the heart of the agency-based corporate finance literature, and Holmström and Tirole (1997) has become a workhorse model for their foundation. We refer, inter alia, to Kaplan and Zingales (1997) for empirical evidence on firm-level financing constraints. Tirole (2010), Döttling and Rola-Janicka (2023), Hoffmann et al. (2017), Oehmke and Opp (2020), and Inderst and Opp (2022) also consider emissions externalities in a framework where firms have limited access to finance. The analysis of Tirole (2010) focuses on the implications of liability, which is constrained by available resources.[9] Oehmke and Opp (2020) and Inderst and Opp (2022) share with us the use of the workhorse model of Holmström and Tirole (1997). Their focus lies, however, on the presence of "green investors", which alleviate financing constraints for more sustainable investment. Hoffmann et al. (2017) do not rely on the Holmström and Tirole model, but instead on an effort-based agency model. An increase in outside financing consequently affects effort and thus the likelihood of firm success, but not investment and thus not industry size and composition, which, because of the associated price effect, are the key margins that we analyze. Also Döttling and Rola-Janicka (2023) model financial constraints differently and find that through its effect on the value of collateralizable assets, a stricter environmental policy may even relax constraints.

Setting an emission tax equal to marginal social cost or the choice of a corresponding cap on tradable emission rights is the textbook Pigou (1932) solution.[10] While the opti-

[9] Predecessors of this work are Boyer and Laffont (1997) and Hiriart and Martimort (2006). This relates also to a larger literature on "judgement proofness" in the presence of limited liability (Pitchford 1995).

[10] For evidence of how a carbon tax on fuel indeed reduces energy consumption, emissions, and economic activity see Martin et al. (2014) and Andersson (2019). Känzig (2021) examines more broadly the impact of carbon-price changes in EU ETS. The practical challenge of an optial carbon tax lies in determining

mality of such a Pigouvian tax has been retrieved also under complex (general equilibrium) scenarios (e.g., Golosov et al. 2014), we acknowledge that the literature has identified rationales, other than financial constraints, for when the socially optimal price of emissions differs from their social cost and when a single instrument is not sufficient. We already referred to the role of market power, which typically leads to an optimal price of emissions below the Pigouvian level (Buchanan 1969, Barnett 1980). In Carlton and Loury (1980) production technologies are non-linear, and the single instrument of a Pigouvian tax no longer secures the social optimum. In the Holmström and Tirole (1997) workhorse model, each firm has a linear investment technology, the scale of production is, however, limited by financial constraints. As we comment below, our key isolated effects hinge on financial constraints and would not arise when (optimal) firm investment was capacity constrained or subject to convex costs. We abstract from possible interactions with other distortionary taxes (Sandmo 1975) or household-level non-separability of externalities in consumption (Diamond 1973, Cremer et al. 1998), which can lead to deviations from the Pigouvian result. Though we noted that, to our knowledge, the implications of firms' financing requirements have not been analyzed yet, the possible role of imperfect capital markets for the choice of optimal environmental policies resonates also in the recent advocacy of Nicholas Stern and Joseph Stiglitz for a broader approach, taking more seriously into account various real-world complexities.[11] Our contribution speaks also to this broader agenda.

The rest of this paper is organized as follows. In Section 2, we describe our model. Section 3 provides a preliminary analysis of the agency problem between firms and investors, and Section 4 derives the market equilibrium. Section 5 analyzes how firm and industry level financial frictions impact on the optimal emission policy. Section 6 considers the

(or agreeing on) the adequate social costs. Their measurement hinges not only on the respective (climate) modeling assumptions, but crucially on the used social rate of discounting (see, for instance, Inderst et al. 2021 for a short overview).

[11] Stiglitz (2019) and Stern and Stiglitz (2021). In the most simple framework, instead, a single emission price is a prerequisite for efficiency (Diamond and Mirrlees 1971).

allocation of emission rights as an additional policy instrument. In Section 7 we discuss multiple industries and endogenous firm abatement activities. We conclude in Section 8. All proofs are collected in the Appendix.

2 The Model

The Economy. For now we envisage a single industry, populated by the potential mass one of firms. The assumption of atomistic firms allows us to abstract from well-known issues related to the interaction between market power and optimal taxation of emissions. We discuss subsequently the extension to multiple industries.[12] Firms are endowed with initial funds, and we initially stipulate that they all share the same size of funds, A.[13] They have access to the same scalable investment technology, albeit firms may differ in their emissions (or their potential to become green, as described below). Denoting the realized investment size of firm i by I_i, total investment equals $I = \int_0^1 I_i di$.

Owner-managers can raise additional funds from households for whom the (marginal) alternative is to store their respective funds. This normalizes the required return to zero. To receive external funds (the size of which we still need to specify), firm i promises a repayment of D_i. The firm will only be able to honor its obligation in case of success.[14] It is here that we bring in an agency problem of external financing, thereby adopting the workhorse model of Holmström and Tirole (1997): The owner-manager needs to monitor the investment technology so as to increase the likelihood of success. To simplify the subsequently derived expressions we suppose that in case of such monitoring, the venture succeeds with probability one. If the owner-manager shirks on monitoring, which is unob-

[12] See also our working paper version, where the entire analysis was conducted with multiple industries.

[13] It is inconsequential whether these are on-going concerns with internal funds (e.g., cash savings) or whether these are potential entrepreneurs with respective own wealth.

[14] It is well-known (and straightforward to show) that we can without loss of generality restrict attention to the case where the owner-manager co-finances the investment with all her funds A, so that, protected by limited liability, she can only repay out of the firm's proceeds (rather than retaining a fraction of A from which repayments can be made as well).

servable to outsiders, she obtains a private benefit per unit of investment $b > 0$, but with probability $q > 0$ the technology fails and returns no output. Output in terms of produced quantity is denoted by x_i, where for simplicity we set $x_i = I_i$ in case of success, while $x_i = 0$ holds in case of failure. As we will show, a sufficient condition for that monitoring is always uniquely optimal is that

$$b < q^2. \tag{1}$$

Aggregating all output x_i to obtain $x = \int_0^1 x_i di$, the per-unit price on the product market is given by the inverse and downward-sloping demand function $P(x)$, with thus $P' < 0$. As each firm has mass zero, its own output does not affect the market price, so that a firm has no strategic incentives to withhold output from the market. In the characterized equilibrium, where each owner-manager has sufficient incentives for monitoring and investments are thus successful, we have $x = I$. We also note that while each firm's investment will always be capped by external financing constraints, investment and output in the aggregate may not be constrained. Still, the equilibrium size of investment will be bounded by marginal profitability, due to the downward-sloping inverse demand $P(x)$.

Output generates negative externalities on society. Firms' technologies can be more or less polluting, captured by the emissions generated per unit of output, which can be high or low, with $y_h > y_l > 0$ (measured in the respective unit, such as tons of CO2 equivalent). A given firm has the respective type y_i, and we denote the fraction of low-polluting firms by μ_l and that of high-polluting firms by $\mu_h = 1 - \mu_l$. It will be useful to aggregate their respective investments as I_l and I_h. We show subsequently that all results continue to hold when firms can reduce emission through endogenous, costly abatement activities.[15]

Social costs of emissions can be monetized, and we suppose that for the relevant spectrum of emissions marginal social costs of emissions are constant and given by $v > 0$.[16]

[15] See also our working paper version, where abatement activities were taken into account throughout the entire analysis.

[16] In the enviromental economics literature frequently also increasing marginal costs of pollution are assumed. This may be realistic both when pollution is mainly local or when in the case of global polluters

With $e_i = x_i v$ and $e = \int_i e_i di$, aggregate social cost of emissions are thus ev.[17] Subsequently, we discuss restrictions on v to ensure that production is socially beneficial.

The Policy Instrument. Our focus lies on the immense financial burden generated by the green transformation. Here, the decarbonization of the economy is at the forefront, and with it the reduction of CO2 emissions. We consider as an environmental instrument a cap-and-trade system, such as the EU Emissions Trading System (EU ETS). There, a cap is set on the total amount that can be emitted by installations covered by the system in a given year. Within the cap, companies receive or buy emission allowances, which they can trade with one another as needed.[18] We thus let the social planner choose a cap K on total emissions. We note that in our baseline model the operation of a cap-and-trade scheme is equivalent to setting a uniform environmental tax.[19] But we will also discuss the role of allocating emission rights under a cap-and-trade system.

Modelling the market for emission rights, we note that also in this market firms are atomistic price takers.[20] We denote by τ the market clearing price per emission right, which will govern investment and thus aggregate emissions e, and it must hold that $e \leq K$. For now we suppose that each firm must acquire the respective rights at the prevailing market price τ. As a consequence, when $x_i = I_i$ (under successful monitoring), a firm's financial need is given by $F_i = I_i(1 + \tau y_i)$, of which the share $F_i - A_i$ needs to be raised externally. While we restrict consideration of policy instruments to the cap-and-trade regime, our subsequent analysis of financial constraints suggests also the use of alternative instruments,

such as greenhouse gases we analyze aggregate pollution even across different economies. Again, our main insights would be unaffected under increasing marginal costs, albeit the loss of a simple Pigouvian benchmark would complicate the interpretation of results.

[17] Social costs are thus also sufficiently diffused so that an individual owner-manager has no private incentives to reduce own externalities.

[18] Under this system they can also buy limited amounts of international credits from emission-saving projects around the world.

[19] Such an equivalence is shown formally in Montgomery (1972). It is however also well known that it does not hold generally e.g., when a social planner faces uncertainty about damages and firms' emission control costs (Weitzman 1974).

[20] Hahn and Stavins (2011) analyze market power in an emission-trading system.

such as subsidies, which target more directly firms' financial needs. We discuss below the limits of such alternative instruments.

With again $x_i = I_i$, the social planner's objective is total welfare

$$\Omega = \int_0^I P(\hat{I})d\hat{I} - \int_i I_i(1 + vy_i)di. \tag{2}$$

The first part captures consumer surplus by means of integration under the inverse demand function P. From this the second part subtracts investment costs as well as social costs of environmental externalities. Levied taxes are considered as a welfare-neutral transfer.

It is instructive to consider, as a benchmark, the first-best outcome. Given the linear production technology, obviously only low-polluting firms, $j = l$, should be active,[21] and marginal social surplus should be zero at total investment and output I, $P(x = I) = 1+vy_l$, which equates marginal consumer welfare to marginal social costs of production.

3 Financial Frictions

It is convenient to provide already here some preliminary analysis of the agency problem of an individual firm. For this we drop the firm subscript i. Recall that an individual firm is a price taker in the product market, where the price is now denoted by p, and in the market for emissions with respective price τ. We next set up the contracting problem between a firm's owner-manager and outside investors. While most of this is standard, the precise timing of the financing of abatement costs and emission rights needs to be tied down. More specifically, we need to stipulate when the respective environmental costs are incurred. We stipulate that the respective costs need to be incurred before output is sold on the market, though they are only realized when the venture is successful and output is indeed realized. When the owner-manager monitors, the venture is successful with probability one, $x = I$.

[21] With the assumed linear technology it is inconsequential whether total output is produced by one firm or by many low-polluting firms.

It is only off-equilibrium, when the owner-manager shirks, that with positive probability these funds are not used. We suppose for this case that investors can secure repayment of these funds, so they cannot be diverted privately by the owner-manager.[22]

In what follows, we first suppose that the financial contract with investors indeed needs to prevent the owner-manager from shirking. In case of success and thus with $x = I$, the owner-manager realizes Ip minus the promised repayment D. This uses that costs related to emissions and their avoidance have already been paid out of raised funds. In case of failure, no output is realized and the owner-manager receives no monetary return. When shirking, failure occurs with probability q, and the owner-manager realizes private benefits bI. To ensure that the owner-manager monitors the technology, comparing the respective payoff to that under shirking, the following incentive constraint must thus be satisfied:

$$Ip - D \geq (1-q)(Ip - D) + bI,$$

which can be transformed to

$$D \leq I(p - b/q). \tag{3}$$

Condition (3) restricts the firm's external financing capacity. This is limited by the agency problem, as expressed by the subtraction of b/q from the product price, as the owner-manager needs to retain a sufficiently high stake in the firm. Otherwise, she would rather realize her private benefits.

We turn now to investors' break-even constraint. Recall that we assumed that households have abundant funds and that the marginal investment alternative is given by a storage technology with zero return. If the incentive constraint is satisfied, so that the owner-manager monitors, investors anticipate to be repaid for sure. Hence, D must at least equal the raised external funds $F - A$: $D \geq F - A$. Substituting for the total funding

[22] Alternatively, we could suppose that the firm always generates output, but that when it fails, output can not be successfully marketed.Such a modification would affect only the condition for when it is indeed optimal to incentivize monitoring, but not the subsequent analysis.

requirement $F = I(1 + \tau y)$, we obtain the break-even constraint

$$D \geq I(1 + \tau y) - A. \tag{4}$$

As the owner-manager is the residual claimant, by optimality the break-even constraint binds. After substitution for D from the thus binding constraint (4), the owner-manager's objective becomes

$$U = I[p - (1 + \tau y)], \tag{5}$$

which is just a formal restatement of her position as the residual claimant: Per unit of investment she realizes the full net marginal return $p - (1 + \tau y)$.

We now return to the incentive constraint (3). There, we substitute from the binding break-even constraint $D = I(1 + \tau y) - A$, which allows to rewrite (3) as

$$I \leq \overline{I} := \frac{1}{b/q - [p - (1 + \tau y)]} A. \tag{6}$$

The right-hand side is only well-defined when the denominator is strictly positive, as only then a firm is financially constrained. Then, the maximally feasible size of the firm's productive investment is equal to a given factor times the owner-manager's own funds A. This is the gist of the agency problem in the Holmström-Tirole workhorse model: It generates binding funding constraints in a tractable way, with a particularly simple (linear) relationship between a firm's own (internal) funds and total feasible investment size.

Maximum firm investment $\overline{I}$ is higher when the firm's (constant) marginal return, $p - (1 + \tau y)$, is higher, as then the cash flow that can be pledged to investors without violating the incentive constraint of the owner-manager is higher. The marginal return on investment is in turn higher, ceteris paribus, when the product price p is higher or when the firm is of a low-pollution type, $y = y_l$. The maximum firm investment $\overline{I}$ is lower when the agency problem is more severe, as b/q is higher, notably when the private benefits b

from shirking are larger.

In our present analysis, the owner-manager's single control is the investment size I (see however the subsequent extension to abatement activities), and we have the following result:

Lemma 1 *For given product price p and given price of emission rights τ, a firm optimally chooses an investment size I^* such that i) $I^* = 0$ when $p < 1 + \tau y$ and ii) $I^* = \overline{I}$ when $p > 1 + \tau y$, while iii) the firm is indifferent between any feasible size from zero to $\overline{I}$ when $p = 1 + \tau y$.*

4 Market Equilibrium

Lemma 1 characterizes firms' individual optimal investment choices. For aggregate investment in equilibrium, we use the notation I_j^* for $j = l, h$ and I^* in the aggregate. In what follows, to reduce case distinctions we want to ensure that also high-polluting firms are active, which is always the case when the fraction of low-polluting firms μ_l is sufficiently low (and K is not chosen too low; see below for a formalization). The characterization of the thereby omitted case will, however, follow immediately from our discussion of a benchmark when $y_l = y_h$.

When thus $I_h^* > 0$ also for high-polluting firms, the marginal net profit must be non-negative also for high-polluters, which implies that the marginal net profit for low-polluters is strictly positive (provided that there is indeed heterogeneity with $y_l \neq y_h$). From Lemma 1 low-polluters must then lever up as much as possible, namely up to $\overline{I}_l$, so that $I_l^* = \mu_l \overline{I}_l$. For high-polluters instead, we need to distinguish between two cases: In one case, also all high-polluting firms lever up maximally, as, in equilibrium, the marginal net return is strictly positive; otherwise, industry size will be determined by a condition of zero marginal return for high-polluting firms. For the latter case, we define the level of total investment at which the marginal return for high-polluting firms is just zero by I_0, solving

$$P(I_0) = 1 + \tau y_h. \tag{7}$$

Next, for given τ, demand for emission rights depends on aggregate investments, $e^* = \sum_j I_j^* y_j$. The market for emission rights clears when either $\tau > 0$ and $e^* = K$ or when $\tau = 0$ and $e^* < K$.

Proposition 1 *Let the social planner choose a cap $K > 0$ on emissions. Then, total investments and with it the outcomes on the product market and the emissions trading market are uniquely determined in equilibrium. Emission rights trade at a unique price $\tau^* = \rho(K)$, which is strictly positive, continuous, and strictly decreasing when $K < \overline{K}$, for some threshold $\overline{K} > 0$. All firms with low pollution, $y_i = y_l$, are active and lever up maximally, $I_i = \overline{I}_l$, giving rise to $I_l^* = \mu_l A \overline{I}_l$. With respect to high-polluting firms, with $y_i = y_h$, the following case distinction applies:*
i) If

$$A \sum_j \frac{\mu_j}{b/q - \tau(y_h - y_j)} \geq I_0, \tag{8}$$

the industry is not financially constrained in the aggregate and $I^* = I_0$. The aggregate investment of high-polluting firms is given by $I_h^* = I_0 - \overline{I}_l$.
ii) Otherwise, the size of industry investment and output is restricted by financial constraints. This is uniquely determined by $I^* = \sum_j \mu_{,j} \overline{I}_j$ and, for $j = l, h$,

$$I_j^* = \overline{I}_j = \mu_j \frac{1}{b/q - [P(I^*) - (1 + \tau y_j)]} A. \tag{9}$$

We briefly discuss condition (8). Firms' (individual and aggregate) inside funds A are a key determinant for whether an industry as a whole is financially constrained. Recall again that we may interpret b/q as capturing the severity of the agency and incentive problem. When A is low, I^* is thus determined by a fixed-point problem. As investment increases, this lowers the prevailing product price and thereby reduces the return that can be maximally pledged to investors. The equilibrium value for investment is just sustained by the then realized maximum pledgable return.

5 Interaction of Financial Frictions and Environmental Policy

With the obtained equilibrium characterization at hands, we can rewrite the social planner's objective function (2) as

$$\Omega = \int_0^{I^*} P(\hat{I})d\hat{I} - I^*(1 + vy_h) + I_l^* v\Delta_y, \tag{10}$$

using $\Delta_y = y_h - y_l$. The three terms in (10) take into account the following components of welfare: first, consumer welfare; second, production and emission costs, as if all investments were undertaken by high-polluting firms; third, the welfare gains that are obtained as a fraction of production is undertaken by low-polluting firms.

We investigate how welfare changes as the social planner adjusts the cap K on emissions, affecting firms' decisions and industry equilibrium through the thereby induced change in the price of emission rights, τ:

$$\frac{d\Omega}{dK} = \rho'(K)\left[\ \tfrac{dI^*}{d\tau^*}\left[P(I^*) - (1 + vy_h)\right] \quad + \quad \tfrac{dI_l^*}{d\tau^*} v\Delta_y\ \right]. \tag{11}$$

Expression (11) decomposes the total impact by considering separately tow margins: the investment margin and the composition margin. For the *investment margin*, the welfare effect depends on how a higher price of emission rights affects total industry size, the investment sensitivity $\frac{dI^*}{d\tau^*}$, and on the social investment benefit, $P(I^*) - (1 + vy_h)$. For the *composition margin*, the welfare effect depends on how a higher price of emission rights affects investment and production of low-polluting firms, the composition sensitivity $\frac{dI_l^*}{d\tau^*}$, and on the social benefit of low polluters (relative to high polluters), $v\Delta_y$. We next focus first on these two margins separately.

Reallocating Market Share to Low-Polluting Firms: The Composition Margin. We first abstract from aggregate financial constraints, so that $I^* = I_0$, as given by (7). That is, case i) of Proposition 1 is supposed to apply over the relevant parameter range. We begin with the following observation: When for $K < \overline{K}$ an increase in K strictly reduces the price of emissions, τ^*, this strictly increases total investment, $dI^*/d\tau^* < 0$.[23]

As a benchmark, suppose now that firms are homogeneous, $y_l = y_h$, so that the last term in (11) drops out from $\Delta_y = 0$. When the price of emissions reaches the Pigouvian level, at $I^* = I_0$ both the private and the social return are zero. Hence, when the industry is not financially constrained in the aggregate and when all firms are equally polluting, a cap that implements the Pigouvian price for emissions realizes the first-best outcome. Denoting the socially optimal level by τ^{**}, we thus have in this case $\tau^{**} = 1$. With heterogeneous firms, however, the composition margin adds an additional effect, on which we now focus.

Making use of high-polluting firms' zero return condition (7), as the industry is not financially constrained in the aggregate, and substituting this into the maximum investment size for low-polluting firms, $\overline{I}_l$, we have

$$I_l^* = \mu_l \overline{I}_l = \frac{1}{b/q - \tau^* \Delta_y} \mu_l A. \tag{12}$$

As the denominator is strictly decreasing in τ^*, given now $\Delta_y > 0$, an increase in the price of emission rights increases low-polluting firms' investment, $dI_l^*/d\tau^* > 0$.

This result holds even though, ceteris paribus, the higher price of emission rights re-

[23] This follows formally from implicit differentiation of (7), as a higher cost of emission rights reduces the marginal profitability of investment.

duces the marginal return of investment also for low-polluting firms. There is, however, a countervailing effect that works through the product market: As total investment I^* decreases, $dI^*/d\tau^* < 0$, this pushes up the prevailing product price $P(I^*)$, easing up financial constraints. For high-polluting firms the two effects, i.e., the direct effect of a higher price of emission rights and the indirect effect of a higher product price, just balance through the condition of a marginal return of zero, $I^* = I_0$. As low-polluting firms are by definition less impacted by a higher price of emission rights, the indirect effect through the product market price dominates, so that their financial constraint eases up and their individual as well as aggregate investment increases.

When we now again choose the cap to reach the Pigouvian benchmark, $\tau^* = v$, in (11) the investment margin is still zero, so that with $\Delta_y > 0$ only the composition margin remains, which is strictly positive: It is thus strictly beneficial to (at least marginally) reduce the cap on emissions and thereby increase the equilibrium price of emissions above the Pigouvian benchmark. We have thus arrived at the following result:

Proposition 2 *Suppose the industry is not financially constrained in the aggregate. When all firms are equally polluting, $\Delta_y = 0$, the socially optimal cap on emissions, K^{**}, should be chosen so that the prevailing price of emission rights just equals the Pigouvian level, $\tau^{**} = v$. When firms are however heterogeneous, $\Delta_y > 0$, the cap should be chosen strictly lower, leading to an emission price strictly exceeding the Pigouvian level, $\tau^{**} > v$, as well as to strictly lower aggregate investment and consequently a strictly higher product price.*

While we presently abstract from aggregate financial constraints, recall that the maximum leverage still remains constrained at the firm level. This limits the share of investment and production accounted for by low-polluting firms. Financial constraints at the firm level are therefore at the heart of the result in Proposition 2, which makes it at first surprising that the optimal policy becomes stricter than the Pigouvian level. We note that this result would not arise when, instead, firm size was (optimally) limited by factors other than financial constraints, such as decreasing returns to scale. Then, $\tau^{**} = v$ would always lead to socially efficient investment at the firm and industry level. We also recall from the Introduction that financial constraints may indeed be of particular relevance for less polluting firms, as, given their novel technology, they may still be relatively opaque to investors and as they may have internal funds or fewer tangible assets in place.

Expanding Investment and Output under Aggregate Financial Constraints: The Investment Margin. When total investment is financially constrained (case ii) in Proposition 1), the investment sensitivity with respect to the price of emission rights is still negative, $dI^*/d\tau^* < 0$ (see formally the proof of Proposition 3). Intuitively, as emission rights become more expensive, with a lower marginal return the maximum pledgable return and thus the maximum leverage decrease.

Recall that without financial constraints at the industry level, at $\tau^* = v$ the marginal social return was just zero at $I^* = I_0$. Instead, when total investment is financially constrained, at the Pigouvian level $\tau^* = v$ the marginal social return is strictly positive, $P(I^*) > 1 + vy_h$. Looking at the investment margin in isolation, it would thus be socially beneficial to reduce the price of emissions so as to expand total investment and output. From this perspective alone, the optimal cap should be strictly below the Pigouvian level. Financial constraints at the industry level thus add a new effect, calling now for a more lenient environmental policy. Before we move on, it is instructive to formalize this insight by again briefly ignoring within-industry heterogeneity.

Proposition 3 *Suppose the industry is financially constrained in the aggregate. When all firms are equally polluting, $\Delta_y = 0$, the socially optimal cap on emissions K^{**} should be chosen so that the prevailing price of emission rights is strictly below the Pigouvian level, $\tau^{**} < v$.*

Countervailing Effects. Recall now the previously identified effect, working through the composition margin, where we abstracted from financial constraints at the industry level. As then the aggregate investment of high-polluting firms was not constrained, but only that of low-polluting effects, the effect working through the higher product price dominated that of a higher price of emission rights only for the low-polluting firms, which pushed up investment and output only for low-polluting firms. This may no longer apply when, instead, both high- and low-polluting firms' aggregate investment, I_h^* and I_l^*, is constrained. Intuitively, for the composition margin effect to still prevail when the industry is financially constrained in the aggregate, both the pecuniary effect from the higher product price and the relative advantage of low-polluting firms must be sufficiently large.

Proposition 4 *Suppose the industry is financially constrained in the aggregate. Then the composition effect still prevails, so that* $\frac{dI_l^*}{d\tau^*} > 0$ *while* $\frac{dI_h^*}{d\tau^*} < 0$*, when*

$$-P'\left(I^*\right)\left(\frac{y_h - y_l}{y_l}\right) > \frac{A\mu_h}{I^*(I_h^*)^2}. \tag{13}$$

Before moving on, we briefly tie together our preceding results. For the composition effect to be effective, which then calls for a more stringent environmental policy, it is essential that less polluting firms are financially constrained. In the Introduction, we reported evidence that this may indeed be the case for firms working with greener technologies. This is in line with the general notion that firms that are younger, i.e., possibly less transparent to the market and endowed with fewer internal funds, or that produce with new technologies find it harder to access external funding.

The case where the industry is financially constrained in the aggregate and where the respective investment effect dominates, calling for a more lenient environmental policy, should instead apply predominantly to economies where financial constraints are overall of greater importance, e.g., as the legal systems provides only inadequate protection for investors (in our model, captured by a more severe agency problem and thus lower pledgability of cash flows). For such economies, starting from the Pigouvian benchmark, at the margin the realization of greater investment and thereby greater consumer welfare is then more important than the avoidance of externalities, and environmental policy should be more lenient. We would argue that, prima facie, this may be of less relevance for economies with a functioning, well developed financial and legal system.

6 The Welfare Effect of Allocating Emission Rights

So far we have assumed that polluters must buy emission rights at the market price resulting from the imposed cap. We now suppose, instead, that the respective rights are initially allocated for free. They can still be traded. Formally, firm i initially receives emission rights R_i. Given some (rationally anticipated) price τ^*, these have the value $\tau^* R_i$. In the absence of financial constraints, such a free allocation would merely represent a transfer and would thus be welfare neutral. This is no longer the case in the presence of financial constraints. Then, as this increases the firm's initial allocation of funds to $A + \tau^* R_i$,[24] it increases firms' maximum feasible leverage.

Let now R_j denote the aggregate allocation of rights to firms of type j, with $j = l, h$. Extending expression (9), the constrained equilibrium investment of firms of type j is given by[25]

$$\overline{I}_j = \mu_j \frac{1}{b/q - [P(I^*) - (1 + \tau y_j)]} (A + \tau^* R_j). \tag{14}$$

When the industry is financially constrained in the aggregate, a free allocation of rights also to high-polluting firms, $R_h > 0$, expands output through the investment margin. Compared to the case where firms have to pay for their emission rights, a free allocation then reduces deadweight loss.

[24] If the market for such rights opens up only after investment has been undertaken, the firm could still borrow funds with claims backed by these rights.

[25] It is straightforward to establish that the same outcome would be obtained when the social planner directly imposed a tax τ and redistributed the respective proceeds to firms according to a regime that is independent of any firm's individual action.

In what follows we focus on the case where financial constraints do not bind in the aggregate. In this case, by relaxing the financial constraint of less-polluting firms, their investment increases when $R_l > 0$. Even when they receive emission rights for free, high-polluting firms do not expand output, but their total investment still decreases, and they sell the rights that they do not use.

The positive effect is present whenever low-polluting firms are allocated rights for free, i.e., even when the initial allocation was uniform across firms or even when this favoured more-polluting firms (under a so-called system of "grandfathering"). However, the positive effect on welfare is higher when the initial allocation is, instead, tilted towards less-polluting firms.

Proposition 5 *Suppose the industry is not financially constrained in the aggregate. Next to imposing a cap on emissions, a policy maker can now also allocate emission rights for free. As long as low-polluting firms receive a positive allocation, $R_l > 0$, this strictly increases welfare by increasing low-polluting firms' output, while that of high-polluting firms decreases (as they trade in any excessively allocated rights, resulting in a welfare-neutral transfer). But the positive effect is higher when the allocation shifts toward low-polluting firms (increasing R_l and decreasing R_h). The allocation is, however, welfare-neutral when firms are homogeneous, $\Delta_y = 0$.*

Comparative Analysis. We now shed additional light on how, in the presence of financial constraints, the allocation of emission rights affects markets. For this we now hold the total allocated quantity K fixed as we switch to a free allocation of rights. In this case, the price of emission rights must decrease and total investment and output must increase. This follows immediately from the following observations. We know that when some emission rights are allocated to low-polluting firms, this relaxes their financial constraints and, ceteris paribus, leads to higher investment and production, at the expense of high-polluting firms, who may sell excessively allocated emission rights. As low-polluting firms produce at less emissions, the total emission quantity K is only fully absorbed when indeed total investment and production increases. From the zero return condition for high-polluting firms, which pins down I^*, this necessarily requires that the price of emissions must decrease. We can also characterize the social planner's optimal response, as follows:

Proposition 6 *Suppose the industry is not financially constrained in the aggregate. Holding first the cap K fixed, when emission rights are initially allocated for free, this leads to a lower price of emissions and to higher aggregate investment and output (and thus also to lower product prices). It is then, however, optimal for the social planner to impose a strictly lower cap.*

7 Extensions

7.1 Endogenous Abatement Activities

So far, firms' unique strategic action was the choice of external financing and with this that of optimal investment and output. We next include an additional (strategic) margin that environmental policy and notably the price of emission rights should govern as well: that of firms' technology choice and abatement activities.

For this we stipulate that a firm can reduce emissions through such abatement activities. The respective reduction is denoted by s_i and comes at costs $c(s_i)$, where $c(0) = c'(0) = 0$ and $c'' > 0$. By choosing $c'(y_l)$ sufficiently high, we ensure a unique interior abatement solution for all firms in the market (i.e., including low-polluting firms that would generate zero emissions per unit of output when choosing $s_i = y_l$). Given output of x_i and abatement activity of s_i, firm i thus generates total emissions $e_i = (y_i - s_i)x_i$ and incurs abatement costs $c(s_i)x_i$.[26]

[26] In the environmental economics literature, also an alternative formalization is used, according to which the firm's activity reduces emissions independent of the realized output, e.g., by ςs_i with associated fixed costs $k(s_i)$ (cf. Lambertini 2017 for an overview of the literature on emission-reducing R&D). As all firms are (product market) price-takers in our model, i.e., as we abstract from strategic interactions on

A firm optimally chooses s_i to minimize marginal costs, $\tau(y_i - s_i) + c(s_i)$, which gives gives rise to s^* solving $c'(s^*) = \tau$. With optimal abatement activity s^*, a firm's funding needs become $F_i = I_i[1+\tau(y_i - s^*) + c(s^*)]$. We can likewise adjust the expressions governing the agency problem and the characterization of the market equilibrium in Proposition 1 simply by adding $c(s^*)$ to marginal costs of investment, which then amount to $1 + \tau(y_i - s^*) + c(s^*)$.

We also need to include abatement activities in the social planner's objective function (10), which expands to

$$\Omega = \int_0^{I^*} P_n(\hat{I})d\hat{I} - I^* \left[1 + \tau(y_h - s^*) + c(s^*)\right] + I_l^* v\Delta_y. \quad (15)$$

Differentiation of Ω thus adds a third margin in (11), next to the investment and composition margin: the abatement margin, given by

$$\frac{ds^*}{d\tau^*} I^* \left[v - c'(s^*)\right],$$

which is the product of abatement sensitivity, $\frac{ds^*}{d\tau^*}$, and social abatement benefits, $I^* \left[v - c'(s^*)\right]$. From implicit differentiation of $c'(s^*) = \tau^*$ at the equilibrium price of emissions, it holds that $\frac{ds^*}{d\tau^*} > 0$: A higher price of emissions pushes up abatement activities.

Consider now Proposition 2, where we stipulated that the industry was not financially constrained. When firms are homogeneous, we found that the socially optimal cap just implements the Pigouvian price for emission rights, $\tau^{**} = v$. This result extends under endogenous abatement activities, given that with this choice s^* is first best as solves $c'(s^*) = \tau^{**} = v$. Recall next that when firms are heterogeneous, the composition margin strictly reduces the socially optimal cap on emission rights, leading to a price of emissions exceeding v. Also this insight extends under endogenous abatement activities, as at $\tau^{**} = v$

the product market, in our analysis it is not of primary importance whether abatement activities affect marginal or fixed costs.

a marginal increase in the price of emissions has a zero first-order effect on the abatement margin (15). Next, for Proposition 3 we stipulated that the industry was financially constrained in the aggregate. When all firms are equally polluting, $\Delta_y = 0$, we found that the social optimal choice now leads to $\tau^{**} < v$. Also this result holds with endogenous abatement activity, given the zero abatement margin at $\tau^{**} = v$. We summarize these results as follows:

Proposition 7 *The preceding results on the optimal choice of environmental policy, Propositions 2 and 3, extend when, next to their level of investment and output, firms can also choose abatement activities to reduce emissions.*

While the addition of an abatement margin thus leaves unchanged the preceding results on a stricter or more lenient environmental policy, it affects quantitatively the optimal price of emission rights, if this differs from the Pigouvian benchmark. More precisely, it adds additional social costs when there is a (non-marginal) deviation from the Pigouvian benchmark, in either direction. Hence, when there is scope for firms to adjust their technology of production or to undertake additional abatement activities, such as the installation of equipment to capture and store greenhouse gases, policy maker should be more hesitant to deviate from the Pigouvian benchmark. Instead, when technologies are fixed or additional abatement activities are less effective, there is greater scope to improve welfare by deviating from the Pigouvian benchmark.

7.2 Multi-Sector Economy

So far we have essentially considered an economy comprising a single industry (with respective output market, described by the inverse demand function $P(q)$). Suppose now instead that the economy is composed of N such industries, each described by an inverse demand P_n, inside assets A_n, a distribution of low- and high-polluters $\mu_{n,j}$, and parameters

(b_n, q_n) characterizing the agency problem between insiders and the providers of external financing. For simplicity we again abstract from the abatement margin.

For a given price of emissions, investment, now per industry, is still uniquely determined, as described in Proposition 1, though the equilibrium price of emissions is now determined by demand from all industries. With total emissions $e = \sum_{n \in N} e_n$, equilibrium emissions are still a strictly increasing function of the emission price, $e^* = \psi(\tau)$, and the equilibrium is pinned down uniquely by $e^* = K$ (when $\tau^* > 0$). The social planner's objective (10) extends by summing up over all industries. With this background, it is now also immediate to see how the previous results extend. When none of the industries is financially constrained in the aggregate and at least one industry is composed of heterogeneous firms, Proposition 2 extends, and the common emission cap should be set stricter than the Pigouvian benchmark. When there is no heterogeneity, so that there is no composition margin, and at least one industry is financially constrained, environmental policy should be relaxed (Proposition 3).

The obvious crux is now, however, that industries might be (even considerably) heterogeneous, in terms of aggregate financial constraints, their composition of more or less polluting firms, or the consumer welfare that is lost by reducing output. With such heterogeneity, social welfare is generically strictly higher when a cap and thereby the price of emission rights is set specifically for each industry (that is, unless the Pigouvian benchmark result applies for each industry). In other words, industry-specific caps should be chosen so as to thereby implement industry-specific emission prices, which optimally trade-off the discussed margins.

Proposition 8 *Suppose now that the economy consists out of $N > 1$ different industries. Unless it was socially optimal to implement for each industry the Pigouvian benchmark, a single emission trading systems is generically suboptimal.*

Prima facie this observation is at odds with notably the working of the EU Emissions

Trading System, which applies to all (non-exempted) industries. But these may have, at least, two explanations. First, also the EU Emissions Trading System is the outcome of a complex political process, and prior to 2022 it was criticized both for its low price for carbon and for its exemptions. Second, a single system may have advantages that our model does not capture, such as greater market liquidity. Still, our analysis may also be of relevance for the further development of this system. While in the past certain (high-polluting) industries have been allocated emission rights for free, this policy is now gradually removed, together with a gradual reduction of the cap.[27] Our analysis suggests, however, a rationale also for an industry-specific allocation of such rights, provided that financial constraints are of relevance, at least for lower-polluting firms. This may indeed become more relevant when the emission cap is considerable reduced and prices of emissions are permanently higher. Such an indirect subsidy, in particular for less polluting firms, has the advantage of being revenue neutral. In our concluding remark we comment on other policy tools.

8 Conclusion

The financial impact of currently undertaken or planned environmental policies will be considerable, and with it firms' need to raise additional financing. In a frictionless market, this would only impact investment to the extent that industry size efficiently readjusts, reflecting the true social benefits and costs of firms' activities. Endogenizing agency costs of external financing, we take a corporate finance perspective on optimal environmental policy. Financial constraints matter at the firm level, as they may constrain the amount of feasible investment notably for low-polluting firms, and they matter as well at the industry level.

Employing the corporate finance workhorse model of Holmström and Tirole (1997),

[27] There were various (not merely politically motivated) reasons for such exemptions, such as to preserve the international competitiveness of domestic industries (and thereby also prevent leakage).

we develop a tractable model that embeds a social planner's choice of aggregate emissions under a cap-and-trade system into an economy where firms need to raise financing, also to cover costs of emission rights and abatement activities, and where the resulting output determines the endogenous product market price. In the benchmark with no financial constraints, adopting the Pigouvian level for the cap on emissions and for the resulting price of emission rights would lead to the efficient outcome along all margins: Industry size and potential abatement activities are efficient, and with heterogeneous technologies only the least-polluting firms operate. Financial constraints generate a wedge between these margins. And with financial constraints also the initial allocation of emission rights matter, as this can mitigate trade-offs along these margins, while otherwise a free allocation would constitute a mere wealth transfer.

In economies with developed financial markets and functioning legal systems, and particularly also for mature industries, which are frequently among the worst polluters, financial constraints may not matter in the aggregate, but still for individual firms, notably younger firms with greener technologies. A price of emission rights that is higher than the Pigouvian level then becomes welfare optimal, as by shrinking aggregate output and thereby pushing up the price on the product market this has a positive pecuniary externality on less-polluting firms, relaxing their financial constraints and thereby increasing their share of total investment. For economies where financial constraints matter in the aggregate, however, welfare is increased by relaxing financing constraints for all firms so as to push up output and increase consumer welfare, in which case a less severe environmental policy should be implemented.

We also pointed to the optimality of sector-specific caps and resulting different prices for emission rights, albeit the resulting benefits could also be realized by a flexible allocation of tradable emission rights. These then alleviate financial constraints for specific (groups of) firms, thereby expanding their share of total output. As each firm is atomistic in our setting, as long as the total industry is not financially constrained, this does not expand total output (with resulting negative implications for total emissions). Such indirect subsidies have the advantage of being revenue neutral. Direct subsidies instead may need to be financed by potentially distortive taxes. And they may have distributional implications, which may need to be accounted for in the social planner's objective function. We leave the analysis of a richer set of instruments under financial constraints to future research. In such a scenario, it could also be of interest to shed more light on firms' perspective, which by becoming more environmentally friendly could tap into specific financial subsidies or attract "green investment".

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A Proofs

Proof of Lemma 1. The constant marginal return from investment, as obtained from differentiating U with respect to I, is $p-(1+\tau y)$. Inspection of the sign of this expression yields the characterization of I^*.

It remains to show that monitoring is indeed uniquely optimal. Without monitoring there is no agency problem that would restrict leverage and thus firm size. Then, the (binding) break-even constraint of investors becomes

$$D(1-q) = I + (1-q)I\tau y - A,$$

where the left-hand side expression takes into account that there is repayment only with probability $1-q$, while for the right-hand side we use that the costs of pollution are only incurred in case of success, when output is sold in the market. Substitution into the owner-manager's expected payoff yields

$$U = (1-q)I[p-(1+\tau y)] - qI + bI.$$

To ensure that a deviation to non-monitoring (without a limitation of scale) is not profitable, it must hold that $dU/dI \leq 0$, which is the case if

$$p-(1+\tau y) \leq \frac{q-b}{1-q}. \tag{A.1}$$

As $b/q - [p-(1+\tau y)] > 0$, this implies (A.1) if $\frac{b}{q} < \frac{q-b}{1-q}$, which transforms to condition (1). **Q.E.D.**

Proof of Proposition 1. Take first τ as given. Aggregate investment I_0, as given by (7), is obtained when, at $p = P(I_0)$, maximum firm investment satisfies

$$\sum_j \mu_j \overline{I}_j \geq I_0. \tag{A.2}$$

When $I^* = I_0$, we can substitute the expression for the (zero) marginal return into $\overline{I}_j$, and condition (A.2) becomes (8).

We consider now the two cases. If (8) holds, $I_l^* = \mu_l A \overline{I}_l$ and $I_h^* = I_0 - \overline{I}_l$ is the unique equilibrium outcome. To see this, note that a higher value of aggregate investment I^* would lead to a strictly negative marginal return for high-polluting firms, so that $I_h^* = 0$, which would contradict $I^* > I_0$. Instead, a lower value of I^* would lead to a strictly positive marginal return also for high-polluting firms, who would then all lever up maximally, which however would contradict $I^* < I_0$. With $I^* = I_0$ the marginal return for high-polluting firms is zero, so that, from indifference, we can indeed specify $I_h^* = I_0 - \overline{I}_l$.

Suppose next that the converse of (8) holds. According to case ii), the equilibrium investments are then characterized as the fixed point (I_n^*, I_h^*) satisfying (9) for $j = l, h$ and $I^* = I_l^* + I_h^*$. This has a unique solution, when interior. To see this, note that for both I_j^* the mapping is continuous and strictly decreasing in I^* and thus from $I^* = I_l^* + I_h^*$

in both arguments. We note, however, that for arbitrary τ the market may not open up, which is where we rely on our stricter condition that also high-polluting firms are active, which we now formalize. This condition can be derived by assuming the converse, in which case $I^* = I_l^* = \mu_l A\overline{I}_l$. The condition thus requires that when only low-polluting firms are present, so that

$$I^* = \mu_l \frac{1}{b/q - [P(I^*) - (1 + \tau y_l)]} A,$$

then $P(I^*) > 1 + \tau y_l$.

We turn next to the market for emission rights. Recall that each firm is a price-taker and that, for given τ, we have uniquely characterized abatement and investment and thereby total emissions. We write this as $e^* = \psi(\tau)$. Monotonicity and continuity of P imply that ψ is continuous and strictly decreasing, both when financial constraints bind in the aggregate and when this is not the case. Define $\overline{\tau} > 0$ so that $\psi(\overline{\tau}) = 0$ and $\overline{K} = \overline{e} = \psi(\tau = 0)$, and finally the inverse function $\rho = \psi^{-1}$. **Q.E.D.**

Proof of Proposition 3. Given the argument in the main text, it thus remains to show formally that $\frac{dI^*}{d\tau^*} < 0$ when the industry is financially constrained. For this we rewrite $I_j^* = \overline{I}_j$ as $I_j^* m_j = \mu_j A$, where $m_j = b/q - [P(I_l^* + I_h^*) - (1 + y_j)]$. We next make some derivations that will be of use also subsequently. Total differentiation of $I_j^* m_j = \mu_j A$ for $j = l, h$ yields

$$\begin{pmatrix} m_l - I_l^* P' & -I_l^* P' \\ -I_h^* P' & m_h - I_h^* P' \end{pmatrix} \begin{pmatrix} dI_l^* \\ dI_h^* \end{pmatrix} = d\tau^* \begin{pmatrix} -I_l^* y_l \\ -I_h^* y_h \end{pmatrix}.$$

Denote

$$D = (m_l - I_l^* P')(m_h - I_h^* P') - I_l^* I_h^* (P')^2 = m_l m_h - P'(m_l I_h^* + m_h I_l^*) > 0$$

from $P' > 0$, and, also after respective transformations,

$$D_l = -I_l^* \left[P' I_h^* (y_h - y_l) + m_h y_l \right]$$

and

$$D_h = -I_h^* \left[P' I_l^* (y_l - y_h) + m_l y_h \right].$$

With

$$D_l + D_h = -(I_l^* m_h y_l + I_h^* m_l y_h) < 0,$$

we thus have

$$\frac{dI^*}{d\tau^*} = \frac{D_l + D_h}{D} < 0.$$

Q.E.D.

Proof of Proposition 4. Using the derivations from the proof of Proposition 3, note first that always $D_h < 0$ and thus $\frac{dI_h^*}{d\tau^*} = \frac{D_h}{D} < 0$. Next, the sign of $\frac{dI_l^*}{d\tau^*} = \frac{D_l}{D}$ is determined by that of D_l and thus strictly positive iff

$$-P' I_n^* I_h^* (y_h - y_l) > m_h y_l,$$

which equals (13) after substituting for $m_h = A\mu_h / I_h^*$. **Q.E.D.**

Proof of Proposition 5. We first compare the outcomes with and without a free allocation of emission rights. When firms must purchase all emission rights, denote by K^{**} the respective welfare-maximizing cap and by τ^{**} and the resulting price of emissions. When we switch to a regime where (some) emission rights are allocated for free, we adjust the respective cap so that the emission price remains unchanged at τ^{**}. As this is not necessarily the optimal choice of the cap when rights are allocated, it is sufficient to show that welfare is still strictly higher in this case. To see this, note that when the price of emissions remains unchanged, $I^* = I_0$ does not change, as it is pinned down by the zero marginal return requirement for high-polluting firms. It thus remains to show that, with fixed I^*, investment of low-polluting firms, I_l^*, strictly increases. But this follows immediately from the extended definition of $\overline{I}_l$ in (14).

When we now compare different allocations of emission rights, say R_j' with R_j'', where $R_l'' > R_h''$, we can proceed likewise, that is starting from the optimal choice of the cap under (R_l', R_h') and, when proceeding to (R_l'', R_h''), adjusting the cap so that the market price of emissions remains unchanged. Again, as the industry is financially unconstrained and as we thereby keep total output unchanged, the change in welfare depends only on the change in $I_l^* = \overline{I}_l$, which from (14) is strictly higher under (R_l'', R_h''). **Q.E.D.**

Proof of Proposition 6. Given the discussion in the main text, it remains to prove the claim regarding the socially optimal cap. For this we consider the derivative of welfare in (11), noting that the term in rectangular brackets must be zero at the optimal choice of the cap and thus at the corresponding emission trading price. When we evaluate this condition at a given price τ^*, as long as the industry is not financially constrained, only the composition margin is affected, that is only the term $\frac{dI_l^*}{d\tau^*} v \Delta_y$. To evaluate this term, we substitute the zero-profit condition for high-polluting firms and expand expression (12) as follows:

$$I_l^* = \overline{I}_l = \frac{\mu_l A}{b/q - \tau^* \Delta_y} + \frac{\tau^*}{b/q - \tau^* \Delta_y} R_l. \tag{A.3}$$

As also the second term in (A.3) is strictly increasing in τ^* and as this is multiplied by R_l, at given τ^* it follows that $\frac{dI_l^*}{d\tau^*}$ is strictly increasing in R_l. When we now start from a given allocation (R_l', R_h') and corresponding optimal cap K^{**} with resulting emission price τ^{**}, so that the first-order condition is satisfied, as we choose $R_l'' > R_l'$ but adjust K to keep the emission price constant, the derivative of Ω with respect to τ^* is strictly positive and, given $\rho'(K) < 0$, the derivative with respect to K is strictly negative. Appealing to strict quasiconcavity, to satisfy the first-order condition under the new allocation (R_l'', R_h''), this requires a reduction of the cap on emissions. **Q.E.D.**