A model of benchmarking regulation: revisiting the efficiency of environmental standards

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Abstract

The conventional economic argument favors the use of market-based instruments over 'command-and-control' regulation. This viewpoint, however, is often limited in the description and characteristics of the latter; namely, environmental standards are often portrayed as lacking structured abatement incentives. Yet contemporary forms of command-and-control regulation, such as standards stipulated via benchmarking, have the potential to be efficient. We provide a first formal analysis of environmental standards based on performance benchmarks. We show, in a variety of contexts, that standards can provide efficient incentives to improve environmental performance.

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1 Introduction

Since the writings of Pigou (1920) and Coase (1960), an important debate has centered around the control of externalities. Parallel to this debate has been the discussion of policy choice; namely, the use of market-based instruments versus 'command-and-control' regulation.[1] Command-and-control regulation is typically criticized on two important grounds: first, for not taking into account varying (marginal) abatement costs—thus not reducing pollution at least cost—and second, for not providing sufficient incentives to develop and adopt new technologies (e.g., Jaffe, Peterson, Portney, and Stavins, 1995; Requate and Unold, 2003; Requate, 2005).[2]

The conventional argumentation in favor of market-based instruments, however, usually assumes command-and-control policies to be at their most restrictive. For example, when comparing cost effectiveness, the conventional comparison usually assumes command-and-control policies provide a uniform emissions limit on all firms. Yet, modern approaches to environmental standards are more sophisticated, which is often not accounted for in policy comparisons. While the development of market-based instruments has received much attention, the same cannot be said for the innovative developments within command-and-control regulation, like introducing flexible emission standards that take differences in abatement cost into account.

Given that most countries still heavily rely on command-and-control policies, standards stipulated via benchmarking have the potential to significantly increase the efficiency of environmental regulation. Nevertheless, while benchmarking regulation has been discussed in environmental policy for more than a decade, the formal modeling of the underlying incentives is sparse. With this article, we contribute to filling that void.

We construct a framework where the division of a rent is conditional on relative environmental performance. As an example, we consider the allocation of operating licenses to potential suppliers on a product market that depends on their adherence to an emissions standard: a firm's operating license determines the level of output it may provide (i.e., its market share), where the scope of the license (i.e., the admissible quantity produced) is larger for lower levels of absolute emissions. More precisely, the scope of firm i's license is determined by its abatement effort relative to the emissions standard, which is defined by the industry's average abatement level.[3] Hence, a firm with relatively clean (polluting) production technology is allowed a larger (smaller) share in total production. In contrast to traditional emission standards, the constraint on emissions in this setup is flexible and incentive-based, which allows firms to both under- and over-pollute relative to the benchmark. Instead of losing their entire concession, heavy polluters are granted a license of smaller scope, whereas the license assigned to overperformers allows a larger scope of production and, hence, market share. To regulate firms, a variety of criteria can

[1] Despite significant advances in the use (and understanding) of market-based instruments over the last five decades, command-and-control regulation remains dominant. Explanations for instrument choice can be seen in, for example, Buchanan and Tullock (1975), Oates et al. (1989), and Aidt and Dutta (2004).

[2] A notable exception is Montero (2002), who finds that standards may offer greater R&D incentives than permits because R&D under standards only reduces a firm's own cost, but not that of its rivals.

[3] Of course, the standard could also be determined by the best available technology or some other benchmark. For example, the EU has recently adopted a benchmarking mechanism to determine free allocation of EU emission allowances (EUAs) under the EU ETS where the benchmark is set to reflect the average performance of the 10 per cent most efficient producers in a given sector (European Commission, 2011). We show, however, that such a strict benchmark may not be needed to ensure strong incentives to abate pollution.

be used. For example, firms' operating licenses could be based on emissions abatement efforts associated with switching between electricity sources (from, say, coal-produced to renewable sources). Thus firms that switch to a larger relative level of renewables are rewarded with an increased scope of the operating license. With cleaner firms serving larger shares of the market, of course, aggregate emissions decrease.

The important aspect of using the industry average as a benchmark is the induced competition in emission abatement. As a relative performance mechanism, benchmarking is thus very similar to yardstick competition (see Shleifer, 1985). In this paper, we adapt the idea of basing regulation on average performance to an environmental context. In contrast to earlier work on yardstick competition, where the regulator observes marginal production cost and sets a price, we allow the regulator to instead observe firms' abatement and regulate polluting production. To analyze the incentive structure of the proposed regulatory scheme, we also draw from the literature on contests (e.g., sporting competitions, R&D races, or conflict), in which the study of relative performance is of primary interest (Konrad, 2009). With the size of firm i's license being dependent on its performance relative to the average abatement efforts of the industry, the license allocation can be modeled as a contest. Doing so enables us to explicitly analyze both the static and dynamic incentives that standards stipulated via benchmarking offer and we demonstrate that these may lead to convergence of marginal abatement costs.

To illustrate the advantages of benchmarking, we extend our basic set-up in three main settings. First, we allow firms to invest in (and adopt) new abatement technologies. We show standards stipulated via benchmarking can be just as efficient in abatement as market-based instruments. Second, we consider a changing market environment and compare total abatement under benchmarking to that under an emission tax. We find that in an expanding market, the proposed standard yields more abatement. Finally, we analyze firms' ability to rent-seek for improved conditions under the environmental standard.[4] Introducing the possibility of rent-seeking behavior, we derive conditions where, even if rent seeking is socially wasteful *per se*, it can improve welfare in equilibrium.

Our results add to the small but growing literature on the design of relative performance mechanisms in environmental regulation (Govindasamy et al., 1994; MacKenzie et al., 2008; D'Amato and Franckx, 2010). In this literature the general emphasis has been on comparing relative performance mechanisms with optimal taxes. For example, both Govindasamy et al. (1994) and D'Amato and Franckx (2010) analyzed (linear) yardstick competition for nonpoint pollution. A general conclusion from this literature is that under emission uncertainty relative performance mechanisms, like benchmarking, can be more efficient than a tax. Intuitively, if there exists a sufficiently large emission error among polluters, stochastic variation can be leveled out via such regulations. Yet, as we show in this paper, even in the absence of stochastic influences, benchmarking regulation can yield considerable gains in efficiency compared to simple emission standards. Therefore, it would be beneficial to implement standards based on benchmarking in a much larger array of applications than previously analyzed.

Our contribution is to formally rationalize the use of benchmarking regulation. When structured abatement incentives are implemented within the regulation—as outlined in this article—command-and-control policies can be effective and may even be more desir-

[4]Related studies on the political economy of environmental regulation have analyzed both how environmental policy is determined via interest groups (e.g., Heyes, 1997; Aidt and Dutta, 2004; Aidt, 2010) as well as the creation of rents from the environmental regulation and the welfare losses incurred from rent-seeking activity (e.g., Dijkstra, 1998; Malueg and Yates, 2006; MacKenzie and Ohndorf, 2012a).

able than an environmental tax. As the majority of environmental policy uses command-and-control regulation, our approach allows policymakers to adjust incumbent prescriptive regulation to provide efficient abatement incentives. Policymakers may prefer this option to installing new (market-based) regulation, which can be both politically and financially costly as the 2011 exit of New Jersey from the Regional Greenhouse Gas Initiative (RGGI) shows. A similar decision was taken by Australia's new government, which retracted the planned cap-and-trade scheme and instead plans to establish a benchmarking command-and-control scheme based on a fixed prize fund that is attributed to firms and project developers according to their relative abatement efforts (see Australian Government - Department of the Environment, 2014). Similar schemes are also in place in the UK—the Non-Fossil Fuel Obligation (NFFO)—and Norway—the Norwegian Carbon Procurement Facility (NorCaP) (see Mitchell, 2000; Nordic Environment Finance Corporation (NEFCO), 2013).

The paper is organized as follows: in the next section, we set up our model of benchmarking regulation and analyze the short-term incentives it provides. In Section 3, we introduce an investment stage and discuss dynamic incentives of benchmarking regulation. Section 4 compares benchmarking to an emission tax, focusing on the abatement incentives the respective instrument provides when the size of the market changes. Section 5 deals with static inefficiencies and political influence. In Section 6 we discuss the applicability of benchmarking regulation and recent policy developments before Section 7 summarizes our findings and concludes.

2 Stipulating environmental standards via benchmarking

2.1 Benchmarking regulation

Let Φ denote the set of profit-maximizing firms engaging in monopolistic competition, where $|\Phi| = n \geq 2$. Production for this market generates pollution. Firm $i \in \Phi$ has the ability to abate this pollution at a cost $C_i(a_i)$, with $C_i'(\cdot), C_i''(\cdot) > 0$, where $a_i \geq 0$ is the abatement level of firm i. In the absence of regulation, the aggregate unrestricted emission level is denoted by $\bar{R} > 0$. We assume that full abatement leads to prohibitively high abatement costs.

Now consider a regulator granting a firm the right to operate on this market conditional on its performance relative to an environmental standard. The corresponding operating license can vary in scope, limiting the amount of production allowed. With lower emissions, a firm is granted a more extensive license, which allows more production and guarantees a larger share in aggregate producer surplus on the output market, denoted as P.[5]

In the following, we assume the environmental standard to be established via benchmarking; more precisely, the benchmark corresponds to the average abatement level of all firms in the market. A firm may receive either more or less than the average share in

[5]A number of alternative interpretations are possible. For example, P could reflect a prize fund that is to be allocated to firms for their relative abatement of pollution (see the discussion section of current policies in Section 6). Additionally, given appropriate function specifications, our framework could be extended to a case where P would be endogenously determined by abatement efforts (see, Chung, 1996), in which case such a model framework could resemble, for example, a tax-and-refund scheme.

aggregate producer surplus depending on its performance relative to the standard. A firm with relatively low emissions is thus rewarded for outperforming rival firms by abating more than the average. In this case, it receives a share greater than $\frac{1}{n}$ of the achievable rent P.[6] At the same time, an underperforming firm with below-average abatement efforts is penalized with a more restrictive operating license and thus a market share less than $\frac{1}{n}$. Obviously, in the absence of collusion, establishing such a standard via benchmarking induces competition in abatement.[7]

Firm i's market share, and thus its reward (or penalty), is determined by an allocation rule $\Gamma(a_i, A)$, where $A = \sum_{i\in\Phi} a_i$ is aggregate abatement. With the environmental standard being based on the average abatement level of firms, the allocation rule Γ deviates from an equal distribution of market shares when abatement efforts are heterogeneous, and this deviation is stipulated by a function φ.[8] $\Gamma(a_i, A)$ hence defines relative individual market shares and can be written as

$$\Gamma(a_i, A) \equiv \frac{1}{n} + \varphi\left(\frac{a_i}{A}\right), \tag{1}$$

where $\varphi(\frac{a_i}{A})$ determines the stringency of the abatement incentives depending on the level of individual abatement a_i relative to total outlays in the industry A. It can be defined by any function $\varphi\left(\frac{a_i}{A}\right)$ satisfying

$$\sum_{i\in\Phi} \varphi(\cdot) = 0,$$
$$\frac{\partial\varphi(\cdot)}{\partial a_i} > 0,$$

for all $i \in \Phi$. These conditions imply the allocation rule Γ is comprised of both rewards and punishments, as

$$\varphi \leq 0 \text{ if } \frac{a_i}{A} \leq \frac{1}{n} \ \wedge \ \varphi > 0 \text{ if } \frac{a_i}{A} > \frac{1}{n}. \tag{2}$$

Hence, within the benchmarking procedure, above-average abatement is rewarded while below-average performance is punished.

Without loss of generality, we restrict our analysis to $n = 2$ firms and define the set of firms $\Phi = \{X, Y\}$.[9] In addition, we assume that in determining rewards and penalties, φ is a function of the difference between individual abatement a_i and average abatement of all firms. Therefore, if the scope of the license is determined via benchmarking, we can define the allocation rule as

$$\Gamma(a_i, A) = \frac{1}{2} + \frac{a_i - \frac{A}{2}}{A} = \frac{a_i}{a_i + a_{-i}} \quad \text{for} \quad i, -i \in \Phi. \tag{3}$$

[6]MacKenzie et al. (2008) briefly discuss this approach in their paper on relative performance mechanisms in pollution permit markets. The relative performance approach will motivate the firms to act strategically. For a general analysis of strategic behavior in contests, see Dixit (1987).

[7]While in a concentrated industry incentives for collusion may exist, yardstick competition can be designed to minimize these incentives, e.g., by imposing restrictions on firms admissible choices (Shleifer, 1985). Therefore, we only consider non-cooperative behavior.

[8]Note that a tax/subsidy scheme could provide equivalent incentives. Given our focus on command-and-control regulation and the fact that such policy would be significantly more complicated than a conventional emission tax, this is not considered here.

[9]The restriction to the two-firm case is purely for ease of representation. As shown in Appendix B, our results extend to the case of $n > 2$.

The extent of a firm's license is thus solely driven by average abatement and deviations from this benchmark. As a result, firm i's choice of abatement indirectly determines its output; the scope of its licensed operations, therefore, also determines its absolute share of producer surplus, ν_i. We assume that a firm choosing not to abate is not eligible for an operating license and is, thus, effectively banned from the market. Interestingly, benchmarking as described in (3) is similar to a standard Tullock contest (Tullock, 1980); a firm's share in producer surplus ν_i for $i \in \Phi$ and $-i \in \Phi \backslash \{i\}$ is thus given by

$$\nu_i(a_i, a_{-i}) = \begin{cases} \frac{a_i}{a_i + a_{-i}} P & \text{if } \max\{a_i, a_{-i}\} > 0, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

Note that for (4) to fully determine market shares, a sufficient condition is that the mark-up per unit of output as well as total producer surplus are constant.[10]

For the remainder, we allow abatement costs to be of the form, $C_i(a_i) = k_i \cdot a_i^2$, where k_i typifies the abatement technology available to the individual firm. The firm's objective then is to choose a_i so as to maximize its payoff function $\pi_i = \nu_i(a_i, a_{-i}) - C_i(a_i)$. Given that $C_i(a_i)$ is continuous and monotonic, its inverse function is well-defined: $C_i(a_i) = c_i \iff a_i = C_i(c_i)^{-1} = k_i^{-\frac{1}{2}} \cdot c_i^{\frac{1}{2}}$. Using the parametrization $m_i = k_i^{-\frac{1}{2}}$, we can rewrite (4) to express i's share in producer surplus as follows:

$$\nu_i(c_i, c_{-i}) = \begin{cases} \frac{m_i c_i^{\frac{1}{2}}}{m_i c_i^{\frac{1}{2}} + m_{-i} c_{-i}^{\frac{1}{2}}} P & \text{if } \max\{c_i, c_{-i}\} > 0, \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

With the attribution rule now being a function of abatement costs, solving the game is straightforward.[11] The firm's optimization determines the equilibrium abatement cost level (denoted by tilde) as

$$\tilde{c}_i = \tilde{c}_{-i} = \frac{P\sqrt{k_i k_{-i}}}{2\left(\sqrt{k_i} + \sqrt{k_{-i}}\right)^2}, \tag{6}$$

which yields the optimal abatement level

$$\tilde{a}_i = \sqrt{\frac{P\sqrt{k_{-i}}}{2\sqrt{k_i}\left(\sqrt{k_i} + \sqrt{k_{-i}}\right)^2}}. \tag{7}$$

The individual equilibrium levels of abatement effort and abatement costs enable us to also derive their respective totals.

Benchmarking regulation results in the following equilibrium levels of aggregate abate-

[10] The proposed instrument would ideally regulate the production of a homogeneous good and, in these circumstances, it seems plausible to assume that producers have similar production costs and, therefore, earn the same mark-up per unit sold. Multiplied with a given demand for the good (or a legally restricted quantity of the output), this mark-up defines the producer surplus, which we hence assume to be constant and exogenous. We relax the first assumption in Section 4.

[11] It is easy to verify that the second-order condition is fulfilled and $\frac{\partial^2 \pi_i}{\partial c_i^2} < 0$.

ment, $\tilde{A}$, and total abatement costs, $\tilde{C}$:

$$\tilde{C} = \tilde{c}_X + \tilde{c}_Y = \frac{P\sqrt{k_X k_Y}}{\left(\sqrt{k_X} + \sqrt{k_Y}\right)^2}, \tag{8}$$

$$\tilde{A} = \tilde{a}_X + \tilde{a}_Y = \sqrt{\frac{P}{2\sqrt{k_X k_Y}}}. \tag{9}$$

With benchmarking regulation, larger values of the exogenous rent P thus provide stronger abatement incentives for both firms. On the other hand, if k_i is large, i.e., if firm i is inefficient in abating pollution, intuitively i abates comparatively little. Depending on the relative efficiency of the abatement technologies available to the two firms, a larger value of the rival's abatement cost parameter k_{-i} may or may not incentivize greater abatement effort by i: when $k_i > k_{-i}$, the higher k_{-i}, the higher are the returns on additional abatement effort by firm i in terms of market share. In contrast, when $k_i < k_{-i}$ and i is thus more efficient in abating pollution, larger levels of k_{-i} motivate relatively less abatement by i due to i knowing of its competitive advantage and anticipating little abatement efforts by the other firm.

In direct contrast to conventional emission standards that require the setting of uniform emission levels among firms independent of their abatement cost, benchmarking regulation leads to a discrimination in abatement efforts. As abatement by the high-cost firm is lower than that by the low-cost firm, standards stipulated via benchmarking are generally more efficient than a conventional emission standard.[12] Nevertheless, as long as firms are heterogeneous in terms of available abatement technologies, benchmarking does not yield the sharing of cost as required by the socially optimal first-best solution, where the sum of aggregate damage from pollution and aggregate abatement cost is minimized. The optimal solution, therefore, requires an equalization of marginal cost, while standards stipulated via benchmarking lead to equal abatement cost, $c_X = c_Y$. The remaining inefficiency can hence be explained by the fact that under benchmarking regulation, the standard (yardstick) is defined by competition over abatement itself rather than its marginal cost. Traditional yardstick competition, on the other hand, reaches efficiency as the regulator observes and compares marginal costs to set the permissible price.

2.2 Relative performance in abatement

To investigate the first-best level of abatement, we introduce a damage function $D(A)$ with $D'(A) < 0$ and $D''(A) > 0$, where $A = a_X + a_Y$. For our purposes, we use a quadratic representation of the damage function given by $D(A) = \frac{(\bar{E} - Ab)^2}{2b}$, where $b > 0$ is a parameter that determines slope and convexity of the damage function, and $\bar{E}$ is the intercept of the marginal damage function. $\bar{E}$ can be interpreted as a parameter determining the *level* of damage, where $\bar{R} = \frac{\bar{E}}{b}$ is the unrestricted level of emissions.

The horizontal aggregation of the individual cost functions yields the aggregate abate-

[12] It is straightforward to show that any level of abatement is achieved at a lower total cost when the regulatory instrument is a standard established via benchmarking rather than a conventional command-and-control policy.

ment cost $C(A)$:

$$C(A) = c_X + c_Y = k_X a_X^2 + k_Y a_Y^2 = \frac{A^2 k_X k_Y}{k_X + k_Y}. \tag{10}$$

The first-best aggregate abatement level, denoted by A^*, is then determined by minimizing the sum of aggregate abatement costs and environmental damage. Solving the first-order condition for A yields the first-best level of aggregate abatement A^*:

$$A^* = \frac{\bar{E}(k_X + k_Y)}{b(k_X + k_Y) + 2k_X k_Y}. \tag{11}$$

To compare A^* with the equilibrium abatement level under benchmarking, $\tilde{A}$, let us define Δ_A as the difference between the first-best aggregate abatement level and the abatement level achieved by benchmarking regulation. Δ_A is thus given by

$$\Delta_A = A^* - \tilde{A} = \frac{\bar{E}(k_X + k_Y)}{b(k_X + k_Y) + 2k_X k_Y} - \sqrt{\frac{P}{2\sqrt{k_X k_Y}}}. \tag{12}$$

Note that Δ_A can be either positive or negative. This indicates that the incentives to abate provided by benchmarking can actually be too strong. Clearly, if the level of damage from unregulated emissions—as determined by $\bar{E}$—is large enough, abatement under benchmarking regulation is lower than the first-best level. In contrast, if the achievable rent P is large, benchmarking provides strong incentives to reduce emissions and as a result, abatement can ultimately reach inefficiently high levels, i.e., over-abatement can occur. This is quite intuitive. As the intensity in individual abatement efforts is driven by the attainable profit, the resulting high degree of competition leads to excessively high levels of abatement compared to the first-best optimum. In the opposite case, when production results in relatively low levels of pollution, the operating license has a low value and thus benchmarking regulation does not incentivize sufficient abatement. Incidentally, Δ_A could also be zero such that benchmarking would lead to the first-best level of abatement. Note, however, that cost-efficiency would not be achieved in this case as long as marginal abatement costs differ.

Whereas equation (12) shows that environmental standards can provide strong incentives for abatement, they are still likely to be inefficient on two grounds: first, they do not reduce abatement at least cost, and second, we show that if abatement technologies are fixed (e.g., regulation is set in the middle of the firm's investment cycle), benchmarking can lead to an additional inefficiency in that it can ultimately incentivize abatement levels exceeding the socially optimal. The remainder of the paper analyses both the incentives of benchmarking regulation to adopt new technologies as well as the impact of the political process on the additional short-term inefficiency.

3 Benchmarking regulation with endogenous technology adoption

The previous section outlined the short-term effects of benchmarking regulation with fixed abatement technologies. Yet an important aspect of policy comparison focuses on dynamic incentives, i.e., the incentives to create and adopt new technologies over time. By defining the industry's average abatement effort as the environmental standard and

allowing the endogenous choice of the technology parameter, k_i, we show the proposed allocation rule Γ provides incentives to create and adopt new abatement technologies.[13]

3.1 Incentivizing investment through benchmarking regulation

To begin, consider an investment function $k_i(I_i)$ that maps individual investment—denoted I_i—to the technology parameter k_i and fulfills $k_i'(\cdot) < 0$ and, therefore, $c_i'(I_i) < 0$. Prior to benchmarking regulation, the firm chooses its investment expenditure to balance the cost of investing in new technologies with the benefits from being able to abate pollution more cheaply. Given the allocation rule Γ is common knowledge, firms have an expectation of the benchmarking outcome when deciding on their investment expenditure in the first stage. We thus solve by backward induction, where the solution to the second stage is analogous to Equation (6). Firm i's optimization problem hence reduces to:

$$\max_{I_i} \pi_i(k_i, I_i), \tag{13}$$

$$\begin{aligned} \text{where } \pi_i(k_i, I_i) &= \nu_i\left(\tilde{c}_i(I_i), \tilde{c}_{-i}(I_{-i})\right) - \tilde{c}_i(I_i) - I_i \\ &= \frac{P\left(2k_{-i}(I_{-i}) + \sqrt{k_i(I_i) \cdot k_{-i}(I_{-i})}\right)}{2\left(\sqrt{k_i(I_i)} + \sqrt{k_{-i}(I_{-i})}\right)^2} - I_i. \end{aligned} \tag{14}$$

Similar to Fu and Lu (2009), we define a class of functions: $k_i(I_i) = \frac{1}{\gamma_i + \mu I_i}$ for $i \in \Phi$ where parameters $\gamma_i \in [0, \infty)$ and $\mu \in (0, \infty)$ are constants. The parameter k_i continues to specify the abatement technology, but γ_i now represents the initial level of technological knowledge. If the firm has a high level of technological knowledge at its disposal, k_i (and thus abatement cost) is relatively small. The parameter μ determines the efficiency of investing in additional knowledge and technological progress. Regardless of the size of μ, investment I_i reduces firm i's abatement cost, allowing to use their expenditure on abatement more efficiently in the ensuing competition in emission abatement.

Solving the maximization problem defined in equation (13) yields an interesting result, which we summarize in the following proposition:

Proposition 1. *Benchmarking regulation with endogenous technology choice—characterized by a class of investment functions $k_i(I_i) = \frac{1}{\gamma_i + \mu I_i}$—may incentivize firms to invest so as to equalize their (marginal) abatement costs, i.e., they invest $I_i^* = \frac{\mu P - 8\gamma_i}{8\mu}$ in order to adopt the same optimal abatement technology given by*

$$k_i^* = k_{-i}^* = \frac{8}{\mu P}. \tag{15}$$

Proof. See Appendix A. □

This result identifies conventional regulation that has the potential to achieve efficiency in abatement without the aid of an emissions tax or tradable licenses. By (repeatedly) basing environmental standards on benchmarking, the regulator can provide incentives for firms to invest in new abatement technologies in order to increase abatement

[13] Note that we do not consider technological spillovers. If they existed in our model, we would expect investment to decrease as spillover effects would reduce the competitive advantage one could gain by investing in a more efficient technology.

and thereby their market shares.[14] Ultimately, firms only differ in their investment decision while their resulting abatement costs—and, therefore, marginal abatement costs—are the same. Just like conventional market-based instruments, stipulating an environmental standard via benchmarking could thus lead to the first-best level of abatement while equalizing marginal abatement costs.

Note that despite obtaining the same share of surplus in the product market, firms' final profits differ. For abatement costs $c_i(k_i^*)$, the profit of firm i is given by $\pi_i^* = \frac{P}{4} + \frac{\gamma_i}{\mu}$ and allows firms with initially more efficient abatement technologies to earn a larger net profit.

3.2 Efficient benchmarking regulation

With investment yielding equal abatement costs, the necessary condition for efficient benchmarking regulation is satisfied. To derive the sufficient condition, we allow the regulator to adjust the allocation rule defined in Equation (3), thereby strengthening (or weakening) the incentives to abate as needed in order to reach the first-best level of abatement.[15] To optimize the incentive structure, the regulator thus increases the rewards (and penalties) awarded for performing better (worse) than the industry average.

A general allocation rule accounting for such alternative incentive structures is given by

$$\Gamma_q = \frac{a_i^q}{a_i^q + a_{-i}^q}, \tag{16}$$

where q is a decision variable of the regulator and enables him to control the strength of the abatement incentives that benchmarking regulation provides. Note that a restriction on q is needed to ensure the mechanism to be consistent in its incentives: as a sufficient condition for an interior solution to exist, we hence introduce the technical assumption that $q < \frac{2}{\ln(\sigma)}$, where σ defines the relative size of k_X compared to k_Y (see Appendix A).

Given the generalized form of the allocation rule Γ_q, total abatement by the two firms now depends on q. Using Equation (16), we can derive equilibrium levels for abatement and abatement costs as well as their respective totals: $\tilde{a}_{i,q}$, $\tilde{A}_q$ and $\tilde{c}_{i,q}$, $\tilde{C}_q$, which are provided in Appendix A. We then introduce investment and—using backward induction with the solution to the second stage given by the equilibrium levels ($\tilde{a}_{i,q}$, $\tilde{A}_q$, $\tilde{c}_{i,q}$, $\tilde{C}_q$)—solve the following optimization problem of firm i:

$$\max_{I_i} \pi_i(k_i, I_i) \tag{17}$$

$$\begin{aligned} \text{where } \pi_i(k_i, I_i) &= \nu_i\left(\tilde{c}_{i,q}(I_i), \tilde{c}_{-i,q}(I_{-i})\right) - \tilde{c}_{i,q}(I_i) - I_i \\ &= \frac{P\left(2k_{-i}^q(I_{-i}) + (2-q)k_i^{\frac{q}{2}}(I_i)k_{-i}^{\frac{q}{2}}(I_{-i})\right)}{2\left(k_i^{\frac{q}{2}}(I_i) + k_{-i}^{\frac{q}{2}}(I_{-i})\right)^2} - I_i. \end{aligned} \tag{18}$$

Taking into account that firms invest so as to equalize marginal abatement costs, the total level of abatement is given by $\tilde{A}_q = \sqrt{\frac{Pq}{2k_X}}$. Equating $\tilde{A}_q$ and the first-best level of

[14] Note that the regulator does not prescribe the use of any specified technology, such as in a regime where best available control technologies (BACT) are used.

[15] Alternatively, to yield the first-best level of abatement, the regulator could simply limit the scope of aggregate operating licenses and thus the rent P.

abatement, A^*, allows us to derive the optimal incentive structure, which we define in the following proposition:[16]

Proposition 2. *Under benchmarking regulation with endogenous technology choice, the regulator can ensure that the first-best level of abatement is reached at minimal abatement costs if the allocation rule in Equation (16) is determined by*

$$q^* = \frac{2\bar{E}^2 k_X}{P(b + k_X)^2}. \tag{19}$$

Naturally, q^* is decreasing in P. Additional incentives via a more convex allocation rule are not needed when P is large. In fact, a value of q^* smaller than one—equivalent to concave payoffs—could be optimal if initial incentives to abate are very strong. The opposite results hold for a large level of damage as determined by $\bar{E}$.

4 Comparing benchmarking regulation and emission taxes

In this section we compare the performance of a standard stipulated via benchmarking to that of an emission tax. As common within the literature on instrument comparisons (e.g., Requate, 2005), we assume that the choice of abatement is independent of the choice of output, i.e., the cost of abatement is a function of a_i and k_i only.

Under an emissions tax, τ, marginal abatement costs are equalized. Thus $\tau = C'(A)$ where $C(A)$ is defined in equation (10). The general form of the abatement level under tax regulation is then given by

$$A_\tau = \frac{\tau(k_X + k_Y)}{2k_X k_Y}. \tag{20}$$

Note that the abatement level under tax regulation is—unlike the abatement level imposed by benchmarking regulation—independent of the value of the rent. The latter implies that in an expanding market, benchmarking could incentivize more equilibrium abatement than an emission tax.

This finding becomes immediate when considering the following: assume that the value of the rent is exogenous, but no longer constant. Instead the product market is expanding (or contracting) and the regulator—and possibly the firms—can anticipate this expansion (contraction). The market growth is denoted $\delta_t \geq -1$ for time period t. The value of the rent is then given by

$$P_t = \varepsilon \cdot (1 + \delta_t)\bar{Q}, \tag{21}$$

where ε is a constant mark-up on the units sold, while $\bar{Q}$ is the exogenous, initial, aggregate number of units that can be sold on the market. By definition, $\delta_0 = 0$, i.e., $P_0 = \varepsilon \cdot \bar{Q}$. Note that the level of unregulated emissions, $\bar{R}_t$, depends on the units sold on the market; therefore, $\bar{R}_t$ is also a function of δ_t and at time t, we have $\bar{R}_t = \bar{R}_t(\delta_t)$ satisfying $\frac{\partial \bar{R}_t}{\partial \delta_t} > 0$.

[16] Just like for a Pigouvian tax, the informational requirement for the optimal incentive structure is extensive, yet our results show the potential of command-and-control regulation to be efficient.

The question we seek to address is how, in a changing market environment, the abatement levels incentivized by benchmarking regulation and emission taxes, respectively, differ from each other. Intuitively, as a relative performance mechanism, benchmarking regulation should motivate more abatement than a tax, which is independent of the abatement of individual firms. To show this, first consider abatement under an emission tax. At time $t = 0$, the emission level under a tax regime is given by $\bar{R}_0(0) - A_\tau$, while at time $t = 1$, remaining emissions are $\bar{R}_1(\delta_1) - A_\tau$. The difference in emissions net of abatement when an emission tax is implemented is thus given by

$$\Delta_\tau = \bar{R}_1(\delta_1) - A_\tau - \bar{R}_0(0) + A_\tau = \Delta\bar{R}, \tag{22}$$

where $\Delta\bar{R}$ is simply the difference between unregulated emissions in periods $t = 0$ and $t = 1$, respectively. If the market is expanding and thus $\delta_1 > 0$, then Δ_τ is positive and emissions increase.

Second, consider the proposed standard stipulated via benchmarking. In a growing market, emissions under this policy regime still increase, however, to some degree, the regulatory instrument automatically adjusts to the new conditions: at time t, remaining emissions are defined by $\bar{R}_t(\delta_t) - \tilde{A}_t$, where—similar to aggregate abatement defined in equation (9)—total abatement is $\tilde{A}_t = \sqrt{\frac{\varepsilon\cdot(1+\delta_t)\bar{Q}}{2\sqrt{k_X k_Y}}} = \sqrt{(1+\delta_t)}\cdot\tilde{A}_0$. Therefore, the difference in remaining emissions under benchmarking regulation between period $t = 0$ and $t = 1$ is given by

$$\begin{aligned}\Delta_B &= \bar{R}_1(\delta_1) - \sqrt{(1+\delta_1)}\cdot\tilde{A}_0 - \bar{R}_0(0) + \tilde{A}_0 \\ &= \Delta\bar{R} - \left(\sqrt{(1+\delta_1)} - 1\right)\tilde{A}_0.\end{aligned} \tag{23}$$

Clearly, if the market is expanding, this difference is again positive. Nevertheless, given there is no change in policy, an environmental standard based on benchmarking is the more sustainable policy in that it leads to more emission abatement than the tax. The latter is due to its inherent incentive structure that motivates additional abatement when attainable producer surplus increases. This finding is summarized in the following proposition:

Proposition 3. *If the regulator implements a permanent policy to regulate emissions and the market is expanding (contracting) at a rate δ_t, an environmental standard stipulated via benchmarking yields more (less) abatement of emissions than an environmental tax. The difference in abatement levels is given by*

$$\Delta_\tau - \Delta_B = \left(\sqrt{(1+\delta_t)} - 1\right)\tilde{A}_0.$$

Growth rate δ_t thus drives the relative advantage (or disadvantage) of benchmarking regulation. Note that—in an expanding market—the incentive to abate more under benchmarking would be enhanced if investment in new technologies was possible. The larger achievable rent would motivate further investment in efficient abatement technologies and, therefore, the resulting abatement under benchmarking regulation would be even greater. On the other hand, if the regulator expects the market to contract, i.e., $\delta_t < 0$, an environmental tax is the more effective policy to reduce emissions as incentives to innovate or to adopt more efficient technologies are reduced.

5 Extension: benchmarking and rent seeking

After considering dynamic incentives of benchmarking regulation, we revisit its potential short-term inefficiencies, namely abatement incentives that exceed the socially optimal. To capture the fact that firms frequently expend effort trying to dilute environmental standards or to receive exemptions from existing regulation, we allow firms the ability to adjust the allocation rule Γ in their favor by investing in rent-seeking effort. We then analyze the impact of rent seeking on the level of total abatement.

5.1 Rent seeking within the allocation rule

Consider a model where the attribution of market shares is not only determined by the scope of the operating license, which depends on abatement effort, but also by individual rent-seeking effort, denoted s_i.[17] The effectiveness of the latter depends on the exogenous parameter $\alpha \in [0,1]$, which alters the degree of influence between abatement and rent-seeking efforts and, therefore, can be seen as a measure of the political system's inherent likelihood to be influenced by rent seeking.[18] For example, with $\alpha = 1$—equivalent to rent seeking having no impact on regulation—the model reduces to that considered in Section 2, whereas $\alpha = 0$ describes a case where political rent seeking is the unique influence on market share. Combining these elements, firm i's absolute share of producer surplus, $\check{\nu}_i$, is now given by:[19]

$$\check{\nu}_i = \begin{cases} \left[\alpha \frac{m_i c_i^{\frac{1}{2}}}{m_i c_i^{\frac{1}{2}} + m_{-i} c_{-i}^{\frac{1}{2}}} + (1-\alpha) \frac{s_i}{s_i + s_{-i}} \right] P & \text{if } \max(c_i, c_{-i}, s_i, s_{-i}) > 0, \\ 0 & \text{otherwise.} \end{cases} \tag{24}$$

As rent seeking is typically assumed to be welfare decreasing, it appears, *a priori,* as if α should always be one: rent seeking should not influence the allocation rule Γ. Yet we prove that optimally $\alpha \leq 1$, i.e., the dilution of *individual* environmental benchmarking regulation through political lobbying may be justified as it can reduce short-term inefficiencies and improve welfare.

Firm i's payoff is given by $\check{\nu}_i(c_i, c_{-i}, s_i, s_{-i}) - c_i - s_i$ and optimization yields the equilibrium levels $\hat{c}_i$, $\hat{s}_i$, and $\hat{a}_i$, which are defined in Appendix A. The associated equilibrium levels of aggregate abatement, $\hat{A}$, abatement cost, $\hat{C}$, and rent seeking, $\hat{S}$, are given by

[17] Rent-seeking efforts are typically viewed as being welfare decreasing. Nevertheless, the second choice variable, s_i, can more generally be interpreted as effort, which could have either positive or negative welfare implications. Yet we show that even if the second instrument is welfare decreasing, its use can still improve welfare overall.

[18] One could think of the regulator having the power to choose α, in which case α would express the regulators valuation of abatement and rent seeking, respectively. Alternatively, one could view α as being exogenous and simply show that $\alpha < 1$ can increase the efficiency of the mechanism. We take the latter approach.

[19] Note that (24) requires a given degree of substitutability between the cost of rent seeking and abatement. For a more general formulation, see Gerigk et al. (2013). An alternative specification would allow both choice variables to be multiplicative; for an example, see Arbatskaya and Mialon (2010).

the following equations:

$$\hat{C} = \frac{\alpha P \sqrt{k_X k_Y}}{\left(\sqrt{k_X} + \sqrt{k_Y}\right)^2}, \tag{25}$$

$$\hat{A} = \sqrt{\frac{\alpha P}{2\sqrt{k_X k_Y}}}, \tag{26}$$

$$\hat{S} = \frac{(1-\alpha)P}{2}. \tag{27}$$

5.2 The welfare effects of rent seeking

As both the abatement and rent-seeking efforts of the firms depend on α, the latter also drives social welfare. To minimize aggregate social costs, we, therefore, determine the second-best optimal level of α. The objective function is given by[20]

$$\min_{\alpha} \; D(\hat{A}) + \hat{C} + \hat{S}, \text{ s.t.} \tag{28}$$

$$\alpha \leq 1, \tag{29}$$

$$\alpha \geq 0, \tag{30}$$

For ease of notation and without loss of generality, we again assume that $k_Y = \sigma k_X$, where σ is defined as before. Our results regarding the optimal level of α are summarized in the following proposition:

Proposition 4. *The optimal level of α is*

$$\alpha^* = \begin{cases} 0 & \text{if } \bar{E} = 0, \\ \dfrac{2\bar{E}^2}{P\sqrt{\sigma k_X^2}\left(-2 + \frac{b}{\sqrt{\sigma k_X^2}} + \frac{4\sqrt{\sigma}}{(1+\sqrt{\sigma})^2}\right)^2} & \text{if } 0 < \bar{E} < \sqrt{P \cdot \Omega}, \\ 1 & \text{if } \bar{E} \geq \sqrt{P \cdot \Omega}, \end{cases} \tag{31}$$

where

$$\Omega = \frac{\sqrt{\sigma k_X^2}}{2}\left(-2 + \frac{b}{\sqrt{\sigma k_X^2}} + \frac{4\sqrt{\sigma}}{(1+\sqrt{\sigma})^2}\right)^2, \tag{32}$$

Proof. See Appendix A. □

Proposition 4 contradicts the intuition that rent seeking, which decreases welfare, should not affect the allocation of market shares in equilibrium.[21] From (31), inefficiencies in benchmarking regulation are driven by the size of the rent P and the level of damage parameter $\bar{E}$. For a low $\bar{E}$, the benefits from abatement are rather small and eventually fall short of its marginal cost. Ultimately, if $\bar{E} = 0$, abatement is unnecessary and ideally

[20] Note that $\hat{S}$ only accounts for the direct monetary cost of rent seeking. If there were additional welfare costs related to rent seeking, of course, the range for which the latter has the potential to increase welfare would be reduced.

[21] Note that this follows from the second-best argument that two distortionary factors may achieve an outcome closer to the first-best outcome.

discouraged by $\alpha = 0$.[22] Similarly, if attainable profit P is large such that $\sqrt{P \cdot \Omega} > \bar{E}$, regulation via benchmarking induces a fierce contest that ultimately leads to abatement efforts exceeding the socially optimal. As the cost of abatement increases exponentially, it can at some point become welfare improving to bear—up to a limit—the social cost of rent seeking instead.

5.3 Total abatement efforts with rent seeking

From Proposition 4, we conclude that $\alpha^* \in (0, 1]$. Hence, we established that rent seeking can increase welfare; however, it remains unclear if the optimal level of rent seeking prevents over-abatement and whether it can even yield the first-best level of aggregate abatement. Considering this question, we find that rent seeking can increase efficiency only if aggregate abatement levels exceed the social optimum. Hence, the optimal level of α can reduce—but not prevent—short-term inefficiencies and thus never yields the first-best level of abatement.[23] These findings are summarized in the following proposition:

Proposition 5. *When α is at its socially optimal level, rent seeking can reduce but never prevent over-abatement of emissions; i.e., we can identify the following parameter ranges:*

- *if $\frac{\bar{E}^2}{P} < \Omega < \Psi$, we have an interior solution where $\alpha^* < 1$ and $A^* < A(\alpha^*)$,*
- *if $\Omega \leq \frac{\bar{E}^2}{P} < \Psi$, we have a corner solution where $\alpha^* = 1$ and $A^* < A(\alpha^*)$, and*
- *if $\Omega < \Psi \leq \frac{\bar{E}^2}{P}$, we have a corner solution where $\alpha^* = 1$ and $A^* \geq A(\alpha^*)$.*

where

$$\Psi = \frac{(b\sigma + b + 2\sigma k_X)^2}{2k_X(1+\sigma)^2\sqrt{\sigma}} \tag{33}$$

Proof. See Appendix A. □

6 Discussion

Our analysis has shown the improved efficiency of command-and-control regulation stipulated via benchmarking. Even in its simplest form, abatement costs are equalized among competitors and hence, any given abatement level is achieved at lower cost than under a conventional standard that prescribes an equal sharing of the abatement target. While the theoretical advantages of benchmarking regulation are thus apparent, this section discusses the practical applicability of our model including informational requirements as well as monitoring and enforcement issues.

Given the importance of firms' abatement levels a_i as the determinant of the scope of their production licenses, it is essential for the regulator to be able to measure a_i.[24]

[22] Of course, regulation would not be needed, thus the proposed mechanism would not actually be employed.

[23] It is easy to show that the results extend to the case with investment.

[24] As is standard in the analysis of environmental regulation, a_i is defined as the difference between emissions from production under a baseline scenario and a scenario in which firm i takes measures to abate its pollution. While this is typically measured per firm, the interpretation of a_i as abatement per unit of production is equally possible.

Furthermore, a definition of the relevant competitors, i.e., defining the bounds of the industry, is typically needed to implement the proposed regulation. While this may appear demanding, environmental policies targeted at certain industries are commonplace and given that the benchmark regulation is best suited for the production of a homogeneous good, defining the industry seems feasible. In such a case—take, for example, the production of electricity—the relevant sector is easily defined and the installation of filter technology or other abatement efforts such as the switch to lower emission combustibles are likely to be observable and could be contracted. Moreover, output data is typically well-documented in annual reports of the producers as well as public data on energy consumption. Hence, when it comes to informational requirements, the main difference from, say, an emission tax, is the need for output data, which, in the example given, is easily available. The measurement of abatement, on the other hand, is similar under both regulatory approaches (as well as other market-based instruments) and can either be monitored directly or calculated based on input use.[25]

With abatement being imperfectly observable, however, firms have an incentive to misreport their actual emissions/abatement. Yet the incentive for false reporting is equally present under any other policy instrument such as emission taxes or cap-and-trade schemes (see, e.g., Harford, 1978; Malik, 1992; Heyes, 2000; Macho-Stadler and Perez-Castrillo, 2006; MacKenzie and Ohndorf, 2012b). Hence, equivalent monitoring and enforcement measures are needed for the proposed benchmarking regulation as are used for conventional regulatory policies and while these may not be able to fully eliminate fraud, the instrument we suggest is no more prone to it than other policies.[26]

Discussing our framework in the context of recent developments in climate policy not only shows how the assumptions of our model can be relaxed, but also how they indeed reflect some elements of contemporary regulation. In particular, accepting the assumption of P being constant seems natural when considering fixed value funds that are used by regulators to pay for pollution abatement. Such schemes exist, for example, in the UK (the Non-Fossil Fuel Obligation, NFFO) and Norway (the Norwegian Carbon Procurement Facility, NorCaP) and a similar instrument is now also introduced in Australia as the new government's flagship climate policy (Australian Government - Department of the Environment, 2014). The Australian Emission Reduction Fund (ERF), which is set to commence on July 1^{st}, 2014, has an annually fixed budget that is shared between firms that abate pollution with larger abaters receiving larger shares of the fund. Our framework, which models the sharing of rent according to relative efforts, may thus assist in the analysis of the incentives underlying these recent policy developments.

Interpreting P as a fixed value fund to finance abatement also changes the informational requirements. While such fund can be sector specific (see the NFFO), the information on the industry would no longer be needed. Instead, given the more general framework of the ERF, monitoring contracted abatement suffices to implement the regulation.

Finally, minor modifications of our model allow for P to be endogenously determined by abatement efforts (see Chung, 1996). Such a framework could then, for example,

[25] An extensive description of possible measurement methods is given in Commission Regulation (EU) No. 601/2012.

[26] Note that firms also have an incentive to simply exceed their legal production limit. This is roughly equivalent to not paying the full amount of emission tax owed or not rendering sufficient emission allowances under a cap-and-trade scheme. We assume such deviation is easily observable and can hence be neglected.

resemble the Swedish NO_X tax scheme in which energy producers first pay a high tax on NO_X emissions before the proceeds of this tax are refunded to the producers according to their relative environmental performance (see, e.g., Sterner and Isaksson, 2006). Clearly, in that case the distributable rent depends on abatement efforts, yet the ensuing sharing of the rent aligns closely with our theoretical model.

7 Conclusion

The purpose of this article is to revisit some of the common criticisms of command-and-control policies by considering more modern forms of environmental standards. For example, benchmarking has often been discussed as a means to improve conventional environmental standards. This sort of mechanism has been advocated by a number of institutions such as UNEP and the World Bank (e.g. Ackermann et al. (1999)), but it has not yet been formalized. We fill this void by modeling the setting of environmental standards based on relative abatement efforts. Building on the theories of contests and yardstick competition, we develop a formal model of environmental standards stipulated via benchmarking and show that command-and-control regulation can both incentivize the adoption of advanced abatement technologies as well as eventually lead to the convergence of marginal abatement costs. Despite the possibility of providing too strong incentives for abatement in the short run when investment in new technologies is not possible, we show that benchmarking regulation is more efficient than conventional standards as the former takes into account firms' varying abatement costs. In addition, the problem of causing over-abatement in the short term is reduced when rent seeking is possible.

Our results, therefore, illustrate that the implementation of environmental standards based on benchmarking may provide a number of benefits to both the firms and the regulator as it not only accounts for firms' varying efficiency in abating pollution, but, unlike conventional command-and-control instruments, may also provide dynamic incentives to reduce emissions over time while reducing the social cost of abatement. Finally, as our discussion of the Australian ERF shows, the validity of our results extends beyond the application to production standards and our framework has the potential to analyze the most recent developments in climate policy when a fixed prize fund is used to incentivize emissions reductions.

A Mathematical appendix

Proof of Proposition 1

Proof. To solve (13) we derive the following set of first-order conditions:

$$\frac{\partial \pi_i}{\partial c_i} = \frac{\mu P \left(\frac{3\left(\frac{1}{\mu I_i + \gamma_i}\right)^{\frac{3}{2}}}{\mu I_{-i} + \gamma_{-i}} + \frac{\sqrt{\frac{1}{\mu I_{-i} + \gamma_{-i}}}}{(\mu I_i + \gamma_i)^2} \right)}{4\left(\sqrt{\frac{1}{\mu I_i + \gamma_i}} + \sqrt{\frac{1}{\mu I_{-i} + \gamma_{-i}}}\right)^3} - 1 = 0 \quad \text{for} \quad i, -i \in \Phi. \tag{A.1}$$

Substitution of the first FOC into the second yields after some simplification

$$\mu I_X + \gamma_X = \mu I_Y + \gamma_Y$$

.

As $k_i = \frac{1}{\gamma_i + \mu I_i}$, it follows

$$k_X^* = k_Y^*. \tag{A.2}$$

Substituting (A.2) into (A.1) yields the optimal level of investment:

$$I_i^* = \frac{\mu P - 8\gamma_i}{8\mu}. \tag{A.3}$$

As $\frac{\partial^2 \pi_i}{\partial I_i^2} < 0$, (A.3) denotes indeed a maximum.

With $k_i = \frac{1}{\gamma_i + \mu I_i}$, (A.3) ultimately defines the cost parameter $k_i^* = \frac{8}{\mu P}$. Finally, substituting (15) into (13) yields the corresponding payoff:

$$\pi_i^* = \frac{P}{4} + \frac{\gamma_i}{\mu}.$$

□

Proof of Proposition 2

Proof. The proof requires solving the game represented by Equation (17) via backward induction. The solution to the second stage is defined by the following first-order condition:

$$\frac{\partial \pi_i}{\partial c_i} = \frac{P q c_X^{\frac{q}{2}} c_Y^{\frac{q}{2}-1} k_X^{\frac{q}{2}} k_Y^{\frac{q}{2}}}{2\left(c_Y^{\frac{q}{2}} k_X^{\frac{q}{2}} + c_X^{\frac{q}{2}} k_Y^{\frac{q}{2}}\right)^2} - 1 = 0.$$

Equating both first-order conditions, we find $c_i = c_{-i}$. Solving the game is then

straightforward and yields:

$$\tilde{a}_{i,q} = \sqrt{\frac{Pqk_i^{\frac{q}{2}-1}k_{-i}^{\frac{q}{2}}}{2\left(k_i^{\frac{q}{2}}+k_{-i}^{\frac{q}{2}}\right)^2}}, \tag{A.4}$$

$$\tilde{A}_q = \frac{\sqrt{Pqk_i^{\frac{q}{2}}k_{-i}^{\frac{q}{2}}}\left(\sqrt{k_i}+\sqrt{k_{-i}}\right)}{\sqrt{2k_ik_{-i}}\left(k_i^{\frac{q}{2}}+k_{-i}^{\frac{q}{2}}\right)}, \tag{A.5}$$

$$\tilde{c}_{i,q} = \frac{Pqk_i^{\frac{q}{2}}k_{-i}^{\frac{q}{2}}}{2\left(k_{-i}^{\frac{q}{2}}+k_i^{\frac{q}{2}}\right)^2}, \tag{A.6}$$

$$\tilde{C}_q = \frac{Pqk_i^{\frac{q}{2}}k_{-i}^{\frac{q}{2}}}{\left(k_{-i}^{\frac{q}{2}}+k_i^{\frac{q}{2}}\right)^2}, \tag{A.7}$$

where $k_i = k_i(I_i) = \frac{1}{\gamma_i+\mu I_i}$.

With the solution to the second stage defined by (A.4) to (A.7), the objective function reduces to (18). Equating the first-order conditions for X and Y yields

$$\left(\frac{1}{\mu I_Y+\gamma_Y}\right)^{\frac{q}{2}}\left(\frac{q+2}{\mu I_X+\gamma_X}+\frac{q-2}{\mu I_Y+\gamma_Y}\right) = \left(\frac{1}{\mu I_X+\gamma_X}\right)^{\frac{q}{2}}\left(\frac{q-2}{\mu I_X+\gamma_X}+\frac{q+2}{\mu I_Y+\gamma_Y}\right),$$

which implies

$$\frac{1}{\gamma_X+\mu I_X} = \frac{1}{\gamma_Y+\mu I_Y}. \tag{A.8}$$

To see this, note that there exists no $\delta \neq 1$ with $\frac{1}{\gamma_X+\mu I_X} = \delta \cdot \frac{1}{\gamma_Y+\mu I_Y}$, for which the first-order condition holds. From (A.8) it directly follows that $k_X = k_Y$.

With this finding, the equilibrium level of total abatement reduces to $\tilde{A}_q = \sqrt{\frac{Pq}{2k_X}}$ and first-best abatement is given by $A_I^* = \frac{\bar{E}}{b+k_X}$. Equating $\tilde{A}_q$ and A_I^*, solving for q^* is straightforward and results in (19).

Note that to ensure consistency of the mechanism's abatement incentives, q is constrained such that total abatement under benchmarking regulation, $\tilde{A}$, increases with higher levels of q; i.e., abatement incentives are consistent iff $\frac{\partial \tilde{A}_q}{\partial q} > 0$:

$$\frac{\partial \tilde{A}_q}{\partial q} = -\frac{P(\sqrt{k_X}+\sqrt{k_Y})\sqrt{k_X^{\frac{q}{2}}k_Y^{\frac{q}{2}}}\left(k_X^{\frac{q}{2}}\left(-2+q\cdot\ln\left(\frac{k_X}{k_Y}\right)\right)-k_Y^{\frac{q}{2}}\left(2+q\cdot\ln\left(\frac{k_X}{k_Y}\right)\right)\right)}{4\sqrt{2Pqk_Xk_Y}\left(k_X^{\frac{q}{2}}+k_Y^{\frac{q}{2}}\right)^2}.$$

Hence, for $k_Y = \sigma k_X$, $\frac{\partial \tilde{A}_q}{\partial q} > 0$ iff

$$k_X^{\frac{q}{2}}\left(2-q\cdot\ln\left(\frac{k_X}{\sigma k_X}\right)\right) > (\sigma k_X)^{\frac{q}{2}}\left(-2-q\cdot\ln\left(\frac{k_X}{\sigma k_X}\right)\right)$$

$$\iff \left(\frac{1}{\sigma}\right)^{\frac{q}{2}} > \frac{q\cdot\ln(\sigma)-2}{q\cdot\ln(\sigma)+2}. \tag{A.9}$$

A sufficient condition for the mechanism to yield consistent incentives to abate pollution is $q \cdot \ln(\sigma) - 2 < 0$ and thus $q < \frac{2}{\ln(\sigma)}$. □

Proof of Proposition 4

Proof. To derive Proposition 4, we proceed with an unconstrained optimization of (28)—where $k_Y = \sigma k_X$—and then derive conditions for potential corner solutions. The unconstrained optimization yields

$$\alpha^* = \frac{2\bar{E}^2}{P\sqrt{\sigma k_X^2}\left(-2 + \frac{b}{\sqrt{\sigma k_X^2}} + \frac{4\sqrt{\sigma}}{(1+\sqrt{\sigma})^2}\right)^2}. \tag{A.10}$$

Hence, for $\bar{E} > 0$, $\alpha^* > 0$, thus there is no corner solution at the lower bound of the domain of α. It is also straightforward from (A.10) that a corner solution $\alpha^* = 1$ exists iff

$$\bar{E} \geq \sqrt{P \cdot \Omega}, \tag{A.11}$$

where

$$\Omega = \frac{\sqrt{\sigma k_X^2}}{2}\left(-2 + \frac{b}{\sqrt{\sigma k_X^2}} + \frac{4\sqrt{\sigma}}{(1+\sqrt{\sigma})^2}\right)^2. \tag{A.12}$$

□

Proof of Proposition 5

Proof. To prove Proposition 5, we first show that for an interior solution of α^*, $A(\alpha^*) > A^*$. For $\alpha^* \in (0,1)$, $A(\alpha^*) < A^*$ iff

$$\underbrace{\frac{\bar{E}(1+\sigma)}{b + b\sigma + 2\sigma k_X}}_{A^*} > \underbrace{\frac{\bar{E}}{\sqrt{\sigma}k_X\left(-2 + \frac{b}{\sqrt{\sigma k_X^2}} + \frac{4k_X\sqrt{\sigma}}{\left(\sqrt{\sigma}k_X + \sqrt{k_X}\right)^2}\right)}}_{A(\alpha^*)}. \tag{A.13}$$

Condition (A.13) simplifies to $1 < -\frac{(1+\sigma)^2}{\sqrt{\sigma}(1+\sqrt{\sigma})^2}$, which never holds. Hence, $\forall \alpha^* \in (0,1)$, $A(\alpha^*) > A^*$.

Second, it is straightforward from (A.11) that $\alpha^* = 1$ iff $\Omega \leq \frac{\bar{E}^2}{P}$, where Ω is defined in equation (32). Finally, from (12) we know that $A(\alpha^* \mid \alpha^* = 1) < A^*$ iff $\Psi < \frac{\bar{E}^2}{P}$, where $\Psi = \frac{(b\sigma + b + 2\sigma k_X)^2}{2k_X(1+\sigma)^2\sqrt{\sigma}}$. This completes the proof. □

B A generalized model with n agents

B.1 The maximization problem of the agents

For completeness, we show the results of the model with rent seeking in a generalized framework with $i = 1, ..., n$ firms. For $i \in \Phi$ and $-i \in \Phi \backslash \{i\}$, the payoff function of the individual is

$$\pi_i = \begin{cases} \left(\alpha \frac{m_i c_i^{\frac{1}{2}}}{m_i c_i + \sum_{-i} m_{-i} c_{-i}^{\frac{1}{2}}} + (1-\alpha) \frac{s_i}{s_i + \sum_{-i} s_{-i}} \right) P - c_i - s_i & \text{if } max\{c_i, c_{-i}, s_i, s_{-i}\} > 0, \\ 0 & \text{otherwise.} \end{cases} \tag{B.1}$$

First- and second-order conditions allow us to solve for the individual and total equilibrium levels of abatement costs, abatement, and rent seeking.

The first derivative of the payoff function (B.1) with respect to c_i is given by

$$\frac{\partial \pi_i}{\partial c_i} = \frac{\alpha P c_i^{-\frac{1}{2}} m_i \left(\sum_{-i} c_{-i}^{\frac{1}{2}} m_{-i} \right)}{2 \left(c_i^{\frac{1}{2}} m_i + \sum_{-i} c_{-i}^{\frac{1}{2}} m_{-i} \right)^2} - 1 = 0.$$

As $c_1 = c_2 = ... = c_i = ... = c_n$, we can calculate c_i, which is given by

$$\hat{c}_{i,n} = \frac{\alpha P m_i \left(\sum_{-i} m_{-i} \right)}{2 \left(m_i + \sum_{-i} m_{-i} \right)^2}.$$

Total abatement costs C are simply given by $\hat{C}_n = n \cdot \hat{c}_{i,n} = \sum_{i=1}^{n} \hat{a}_{i,n}^2 k_i$.

As we have established that $a_i = \left(\frac{c_i}{k_i} \right)^{\frac{1}{2}}$, we can easily compute individual and total abatement levels, i.e., $\hat{a}_{i,n}$ and $\hat{A}_n = \sum_{i=1}^{n} \hat{a}_{i,n}$.

The equilibrium level of rent seeking $\hat{s}_{i,n}$ is derived by using the first-order condition of the payoff function with respect to s_i:

$$\frac{\partial \pi_i}{\partial s_i} = (1-\alpha) P \frac{\sum_{-i} s_{-i}}{s_i + \left(\sum_{-i} s_{-i} \right)^2} - 1 = 0.$$

Given that $s_1 = s_2 = ... = s_i = ... = s_n$, we have

$$\hat{s}_{i,n} = \frac{(1-\alpha) P (n-1)}{n^2}.$$

Aggregate rent seeking is given by the sum of the $\hat{s}_{i,n}$: $\hat{S}_n = \sum_{i=1}^{n} \hat{s}_{i,n} = n \cdot \hat{s}_{i,n}$.

To summarize, if payoffs are defined by (B.1), the equilibrium is defined by

$$\hat{c}_{i,n} = \frac{\alpha P \left(\sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)}{2\sqrt{k_i} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2},$$

$$\hat{C}_n = \sum_{i=1}^{n} \frac{\alpha P \sum_{-i} \frac{1}{\sqrt{k_{-i}}}}{2\sqrt{k_i} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2},$$

$$\hat{a}_{i,n} = \sqrt{\frac{\alpha P \left(\sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)}{2k_i^{\frac{3}{2}} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2}},$$

$$\hat{A}_n = \sqrt{\frac{\alpha P}{2}} \cdot \sum_{i=1}^{n} \sqrt{\frac{\left(\sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)}{k_i^{\frac{3}{2}} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2}},$$

$$\hat{s}_{i,n} = \frac{(1-\alpha)P(n-1)}{n^2},$$

$$\hat{S}_n = \sum_{i=1}^{n} \hat{s}_{i,n} = n \cdot \hat{s}_{i,n} = \frac{(1-\alpha)P(n-1)}{n}.$$

B.2 Welfare optimization

We now determine the optimal α_n by minimizing the costs to society:

$$\begin{aligned} &\min_{\alpha} \left[D(\hat{A}_n) + \hat{C}_n + \hat{S}_n \right], \\ &\text{s.t. } 0 \leq \alpha \leq 1, \end{aligned} \tag{B.2}$$

where

$$D(\hat{A}_n) = \frac{\left(\bar{E} - \sqrt{\frac{\alpha P}{2}} \cdot \sum_{i=1}^{n} \sqrt{\frac{\left(\sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)}{k_i^{\frac{3}{2}} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2} b} \right)^2}{2b},$$

$$\hat{C}_n = \frac{\alpha P}{2} \sum_{i=1}^{n} \frac{\sum_{-i} \frac{1}{\sqrt{k_{-i}}}}{\sqrt{k_i} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2},$$

$$\hat{S}_n = \frac{(1-\alpha)P(n-1)}{n}.$$

Rearranging the first-order condition allows one to solve for the interior solution of the optimal α in the n-player case:

$$\alpha_n^* = \frac{2\bar{E}^2 \left(\sum_{i=1}^n \sqrt{\frac{\sum_{-i} \frac{1}{\sqrt{k_{-i}}}}{k_i^{\frac{3}{2}} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2}} \right)^2}{P \left(-4 + \frac{4}{n} + b \left(\sum_{i=1}^n \sqrt{\frac{\sum_{-i} \frac{1}{\sqrt{k_{-i}}}}{k_i^{\frac{3}{2}} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2}} \right)^2 + 2 \sum_{i=1}^n \frac{\sum_{-i} \frac{1}{\sqrt{k_{-i}}}}{\sqrt{k_i} \left(\frac{1}{\sqrt{k_i}} + \sum_{-i} \frac{1}{\sqrt{k_{-i}}} \right)^2} \right) \right)^2}.$$

It is easy to check that this is equivalent to the results of the case with two firms. Therefore, the underlying incentives remain unchanged.

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