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Environmental policy, technology adoption and the size distribution of firms☆

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ABSTRACT

The potential impacts of strict environmental policies on production costs and firms' competitiveness are central to the choice of which policy to implement. However, not all the industries nor all firms within an industry are affected in the same way. In this paper, we investigate the effects of emission taxes, uniform emission standards, and performance standards on the size distribution of firms. Our results indicate that, unlike emission taxes and performance standards, emission standards introduce regulatory asymmetries favoring small firms. On the contrary, emission taxes and performance standards reduce to a lower extent profits of larger firms but they do modify the optimal scale of firms. We also show that when the regulatory asymmetries created by emissions standards are taken into account, the profitability of emissions reducing technologies is higher under emission standards than under market-based instruments.

1. Introduction

Climate change mitigation necessitates the implementation of stringent environmental regulations to control emissions of greenhouse gases. For instance, the successful implementation of the 2030 climate and energy targets in EU requires at least 40% cuts in greenhouse gas emissions (from 1990 levels) and 27% improvement in energy efficiency. The 40% target will only be achieved if EU emissions trading system sectors (ETS) cut emissions by 43% and non-ETS cut emissions by 30% (compared to 2005). The ETS has to be reformed in order to achieve the first target, while achieving the second target requires that Member States implement additional measures to cut emissions and increase the energy efficiency of the non-ETS sectors.

The potential impacts of strict environmental policies on employment, production costs and firms' competitiveness are central to the choice of which policy to implement. Not all the industries will be affected in the same way. For instance, energy-intensive industries that emit larger quantities of greenhouse gases face higher costs from environmental regulations that require firms to pay for the cost of emissions, which can undermine their competitiveness to a greater extent than non energy-intensive industries (see e.g. Aldy and Pizer, 2015; Alexeeva-Talebi et al., 2012). Furthermore, not all the firms in an industry will be affected in the same way. In particular, small firms might be at a disadvantage if there are scale economies in regulatory compliance. In such a case, it might be optimal to exempt or impose lighter regulatory burden on smaller firms, or design regulations that are neutral across firm size to minimize the disproportionate impact of environmental regulatory requirements on small businesses (e.g., Brock and Evans, 1985).

In this paper, we investigate the effects of the choice of policy instruments on the size distribution of firms when compliance with environmental regulation changes the optimal plant size. By this means, we contribute to the understanding of the differential

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effect of regulation across firm size, which is important since societies often have an interest in preserving small businesses because of antitrust or other noneconomic reasons (see e.g., Evans, 1986). Furthermore, understanding the incidence of regulatory costs across firm size allows us to anticipate the interest of certain groups of businesses in supporting alternative regulatory policies. Our paper compares three broadly used environmental policies, namely emission taxes, emission standards, and performance standards. We show that unlike emission taxes and performance standards, emission standards induce regulatory asymmetries favoring small firms. Moreover, unlike previous studies suggesting that market-based instruments create more effective technology adoption incentives than conventional regulatory standards, our results indicate that when the regulatory asymmetries created by emissions standards are taken into account, the profitability of emission saving biased technological change is higher under emission standards than under market-based instruments.

The size distribution of firms has been extensively studied in the industrial organization literature. Most of the literature deals with the distributional properties of firm size (see, e.g., Cabral and Mata, 2003; Angelini and Generale, 2008). However, more recent research has integrated the size distribution of firms into standard economic theory. Attempts to explain the size dynamics have investigated the effects of bad productivity shocks (Hopenhayn, 1992; Ericson and Pakes, 1995), learning (Jovanovic, 1982), inefficiencies in financial markets (Clementi and Hopenhayn, 2006), the exogenous distribution of managerial ability in the population (Lucas, 1978; Garicano and Rossi-Hansberg, 2004), and the efficient accumulation and allocation of factors of production (Rossi-Hansberg and Wright, 2007).

In the environmental economics literature, the effects of alternative environmental policies on market structure have also been investigated (see Millimet et al., 2009 for a survey of theoretical and empirical studies on the economic effects of environmental regulations on market structure). A common finding of this literature is that in competitive markets, emission taxes and (auctioned) emissions trading schemes induce efficient entry of firms in the long run, whereas subsidies on abatement and uniform emission standard policies would distort the entry-exit conditions and induce excessive entry (see e.g., Spulber, 1985; Katsoulacos and Xepapadeas, 1996; Kohn, 1997). Such result might, however, not hold in the case of non-competitive markets (see e.g., Shaffer, 1995). Moreover, the effects on firms' output are unclear and depend on the elasticity of the demand function for the final product (see e.g., Conrad and Wang, 1993; Kohn, 1997). Some studies have also analyzed the effects of certain environmental regulations on industry dynamics. For instance, Konishi and Tarui (2015) and Dardati (2016) investigate the effects of different allocation rules of non-auctioned emission trading schemes on the size distribution of firms, and closing of plants and new entrants, respectively, finding that if permits are not distributed in a manner that disproportionally favors dirtier firms, the distribution of firms after the implementation of the policy has cleaner and more-productive plants.

Our study is, however, closer to earlier studies which have identified two counteracting effects through which environmental policies affect the distribution of size. First, the studies by Pashigian (1984), Dean et al. (2000), and Sengupta (2010) indicate that due to economies of scale, environmental regulation modifies the optimal scale of firms and puts small firms at a unit cost disadvantage. Second, Becker et al. (2013) argue that there are statutory and/or enforcement asymmetries that favor smaller establishments. Hence, the final incidence of environmental regulations depends on whether these regulatory asymmetries outweigh any scale economies in regulatory compliance.

Our study shows that the relative magnitude of these two effects is dependent on the type of environmental policies in place. Under emission taxes and performance standards, the intensity of emissions is determined by the stringency of the regulation and it is the same across firms. In contrast, under emission standards, the regulatory goal is expressed as an absolute emission limit, which favors smaller firms as the limit might not bind their emissions. Our results indicate that emission taxes and performance standards do not introduce regulatory asymmetries, but do modify the optimal scale of the firms. Moreover, the existence of economies of scale implies that these policies reduce to a lower extent profits for larger firms than for smaller firms. In contrast, under emission standards the incidence of the regulatory costs across firm size depends on the two counteracting effects described above, but the final effect is that emission standards reduce the profits of large firms to a larger extent. Moreover, our study shows that when the regulatory asymmetries created by emission standards are taken into account, the profitability of abatement technologies is higher under emission standards than under market-based instruments since the most productive firms (which are likely to invest in new technologies), are more constrained under emission standards. To the best of our knowledge, such a result is new in the literature, and finds some empirical support in the studies by Klemetsen et al. (2016) and Bye and Klemetsen (2018), which find that emission standards induce costs that involve a limit on production activity for the firms, providing strong and persistent incentives for innovation and adoption of new technologies.

To study the effects of the choice of policy instruments on the size distribution of firms, we follow the seminal model by Lucas (1978), where the underlying size distribution of firms in the industry is the result of the existence of a productive factor of heterogenous productivity. In Lucas' model, such a factor is the managerial technology, while in ours it is the energy efficiency of firms.[1] In such a setting, we introduce different environmental policies and analyze the resulting size distributions, as well as the variations in size distribution that arise as a result of investments that reduce the cost of compliance with environmental regulations.

The paper is organized in six sections. The next section presents the model and the underlying size distribution of firms in the absence of environmental policies. The third section analyzes the incidence of regulatory costs across size and how the choice of a policy instrument modifies the size distribution of firms. The fourth section analyzes the effects of the choice of policy instruments on the share of the polluting input and technological choice. The fifth section presents some numerical simulations and analyzes welfare implications. The final section concludes.

2. The model

We assume a perfectly competitive stationary industry consisting of a continuum of risk-neutral single-plant polluting firms of mass 1. Firms produce a homogeneous good using two inputs: energy (e) and labor (l). Moreover, each unit of energy e used as an input generates γ units of emissions ξ, i.e., $\xi_i = \gamma e_i$. Firms differ in terms of the parameter ϕ, which reflects energy efficiency and is assumed to be uniformly distributed on the interval $\left[\underline{\phi}, \bar{\phi}\right]$.

[1] Our model also resembles that of Melitz (2003), who derives a simple model of industry equilibrium in an open economy with heterogeneous firms. Firms differ in terms of their marginal productivity of labor (the only factor of production). The productivity of each firm is randomly drawn from some distribution, but unlike our model, firms do not know their productivity prior to starting production. One of the predictions of the Melitz model is that opening up to trade will increase aggregate productivity.

Assuming a Cobb–Douglas technology, the production function of firm i is then characterized as:

$$q(\phi_i, e, l) = \theta[\phi_i e_i]^{\alpha} l_i^{\beta} \quad \vee\, \alpha, \beta > 0,\ \alpha + \beta < 1, \tag{1}$$

where q is the amount of output produced by a firm using e units of energy and l units of labor, ϕ_i is the energy efficiency of firm i, and θ is a technology index. In the absence of environmental regulation, firm i maximizes net profits π_i^{NR} through the choice of inputs:

$$\max_{e_i, l_i} \pi_i^{NR} = p\theta[\phi_i e_i]^{\alpha} l_i^{\beta} - wl_i - ze_i - F, \tag{2}$$

where w and z are the equilibrium wage rate and energy price, respectively. p represents the output price, and F corresponds to a fixed cost. The first order conditions (FOCs) for the choice of inputs (e_i^{NR}, l_i^{NR}) are given by:

$$p\alpha\theta\phi_i^{\alpha} e_i^{\alpha-1} l_i^{\beta} = z, \tag{3}$$

$$p\beta\theta\phi_i^{\alpha} e_i{}^{\alpha} l_i^{\beta-1} = w. \tag{4}$$

Dividing by parts, we obtain:

$$\frac{e_i^{NR}}{l_i^{NR}} = \frac{\alpha w}{\beta z}. \tag{5}$$

Substituting Eq. (5) in the FOCs, we can solve for e_i^{NR} and l_i^{NR} as:

$$e_i^{NR} = \left[p\theta\beta^{\beta} w^{-\beta} \alpha^{1-\beta} z^{-[1-\beta]} \phi_i^{\alpha}\right]^{\frac{1}{1-\alpha-\beta}}, \tag{6}$$

$$l_i^{NR} = \left[p\theta\beta^{1-\alpha} w^{-[1-\alpha]} \alpha^{\alpha} z^{-\alpha} \phi_i^{\alpha}\right]^{\frac{1}{1-\alpha-\beta}}. \tag{7}$$

We assume that $2\alpha + \beta < 1$, which means that the demand of energy is a concave function of the energy efficiency.

Replacing Eqs. (6) and (7) in Eqs. (1) and (2), we can solve for the output and profits of firm i as:

$$q_i^{NR} = \left[p^{\alpha+\beta}\theta\beta^{\beta} w^{-\beta} \alpha^{\alpha} z^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}} \phi_i^{\frac{\alpha}{1-\alpha-\beta}}, \tag{8}$$

$$\pi_i^{NR} = [1-\alpha-\beta]\left[p\theta\phi_i^{\alpha}\beta^{\beta} w^{-\beta}\alpha^{\alpha} z^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}} - F. \tag{9}$$

From Eqs. (8) and (9), it is possible to see that output and profits increase as energy efficiency ϕ_i increases. Firm i would operate in this market as long as its profits are larger than F. Consistent with this, in the continuum of firms the minimum energy efficiency ϕ_0^{NR} satisfies the condition $\pi^{NR}(\phi_0) = F$, or:

$$\phi_0^{NR} = \left[\frac{F^{1-\alpha-\beta} z^{\alpha} w^{\beta}}{p\theta\beta^{\beta}\alpha^{\alpha}[1-\alpha-\beta]^{1-\alpha-\beta}}\right]^{\frac{1}{\alpha}}. \tag{10}$$

Thus, the energy efficiency of the firms operating in the market is uniformly distributed on the interval $\left[\phi_0^{NR}, \bar{\phi}\right]$, where $\phi_0^{NR} \geq \underline{\phi}$. Note that ϕ_0^{NR} is an increasing function of the inputs prices z and w and a decreasing function of the output price p and the technology index θ. Moreover, the existence of the cost F implies economies of scale since large firms can spread the fixed cost across more output units than small firms.

We can compute aggregate emissions in the absence of environmental regulation Σ^{NR} by integrating emissions of firm i, ξ_i, over the range $\left[\phi_0^{NR}, \bar{\phi}\right]$, which leads to:

$$\Sigma^{NR} = \gamma \int_{\phi_0^{NR}}^{\bar{\phi}} \left[p\theta\beta^{\beta} w^{-\beta}\alpha^{1-\beta} z^{-[1-\beta]}\right]^{\frac{1}{1-\alpha-\beta}} \phi_i^{\frac{\alpha}{1-\alpha-\beta}} d\phi. \tag{11}$$

Let $h = \frac{1-\beta}{1-\alpha-\beta} > 1$ and $k_1 = \left[p\theta\beta^{\beta} w^{-\beta}\alpha^{1-\beta} z^{-[1-\beta]}\right]^{\frac{1}{1-\alpha-\beta}}$. The solution to Eq. (11) can be represented as:

$$\Sigma^{NR} = \frac{\gamma k_1}{h}\left[\bar{\phi}^h - \left[\phi_0^{NR}\right]^h\right]. \tag{12}$$

To compute total output with no regulation Q^{NR}, we integrate Eq. (8) over the interval $\left[\phi_0^{NR}, \bar{\phi}\right]$, which leads to:

$$Q^{NR} = \frac{z}{\alpha p\gamma}\Sigma^{NR} \quad .$$

Dividing individual emissions γe_i^{NR} in Eq. (6) by individual output q_i^{NR} in Eq. (8), we can see individual emission intensity in the absence of environmental regulations correspond to $\frac{\alpha p\gamma}{z}$. Note that it coincides with the average emission intensity of all firms in the economy, Σ^{NR}/Q^{NR}. Moreover, (individual and average) emission intensity is a decreasing function of the price of energy z. It is also an increasing function of the share of energy in the production process α and of the output price p. Furthermore, the lower the coefficient γ, the lower the emission intensity.

3. Environmental regulation

Let us now analyze the effects of environmental policies on the size distribution in equilibrium. We assume that given the initial size distribution of firms, the regulatory goal is to limit aggregate emissions at some level $\bar{E}$. The regulator implements the environmental target by means of one of the following three regulatory instruments: a per-unit emission tax τ, a uniform emission standard $\bar{\xi}$, and a uniform performance standard that defines the maximum intensity of emissions κ. Finally, we assume that the stringency of each policy remains unchanged regardless of the effects of the instruments on the initial size distribution of firms.

3.1. Optimal environmental regulation

We first determine the optimal stringency of the environmental regulation before examining to what extent will the different policy instruments implement such first best (FB). Social welfare W is given by aggregate profits less environmental damages. The social damage function is given by $D(\Sigma)$, where Σ denotes the aggregate emissions generated by the active firms $\phi_i \in \left[\phi_0^{FB}, \bar{\phi}\right]$, and ϕ_0^{FB} corresponds to minimum energy efficiency of an active firm at the optimum (i.e., $\Sigma = \gamma\int_{\phi_0^{FB}}^{\bar{\phi}} e_i(\phi_i)d\phi_i$). The damage function $D(\Sigma)$ is assumed to be differentiable with $D'(\Sigma) > 0$ and $D'(\Sigma) \leq 0$. As our goal is to characterize the optimal regulatory stringency, we assume that the regulator aims to maximize social welfare W given by:

$$\max_{e_i, l_i}\ W = \int_{\phi_0^{FB}}^{\bar{\phi}} \left[p\theta\phi_i^{\alpha} e_i^{\alpha} l_i^{\beta} - wl_i - ze_i - F\right] d\phi_i - D(\Sigma).$$

Finding the FOCs for the optimal choice of inputs (e_i^{FB}, l_i^{FB}) yields:

$$p\alpha\theta\phi_i^{\alpha} e_i^{\alpha-1} l_i^{\beta} = z + D'(\Sigma)\gamma,$$

$p\beta\theta\phi_i^\alpha e_i^\alpha l_i^{\beta-1} = w.$

Dividing by parts, we obtain:

$$\frac{e_i^{FB}}{l_i^{FB}} = \frac{\alpha w}{\beta\,[z + D'(\Sigma)\gamma]}.$$

Substituting the last equation in the FOCs, we can solve for e_i^{FB} and l_i^{FB} as:

$$e_i^{FB} = \left[p\theta\beta^\beta w^{-\beta}\alpha^{1-\beta}[z + D'(\Sigma)\gamma]^{-[1-\beta]}\phi_i^\alpha\right]^{\frac{1}{1-\alpha-\beta}}.$$

$$l_i^{FB} = \left[p\theta\beta^{1-\alpha} w^{-(1-\alpha)}\alpha^{\alpha}[z + D'(\Sigma)\gamma]^{-\alpha}\phi_i^\alpha\right]^{\frac{1}{1-\alpha-\beta}}.$$

The individual output and profit functions are then given by:

$$q_i^{FB} = \left[p^{\alpha+\beta}\theta\beta^\beta w^{-\beta}\alpha^{\alpha}[z + D'(\Sigma)\gamma]^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}},$$

$$\pi_i^{FB} = [1-\alpha-\beta]\left[p\theta\phi_i^\alpha\beta^\beta w^{-\beta}\alpha^{\alpha}[z + D'(\Sigma)\gamma]^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}} - F.$$

Hence, the cutoff value that satisfies the condition $\pi\left(\phi_0^{FB}\right) = F$ yields:

$$\phi_0^{FB} = \left[\frac{F^{1-\alpha-\beta}[z + D'(\Sigma)\gamma]^\alpha w^\beta}{p\theta\beta^\beta\alpha^\alpha[1-\alpha-\beta]^{1-\alpha-\beta}}\right]^{\frac{1}{\alpha}}. \tag{13}$$

This zero profit condition requires that the cutoff value ϕ_0^{FB} is such that private profits equal the marginal social damage of emissions plus the fixed cost. As advocated by Spulber (1985), the FB could be implemented through an emission tax equal to $\tau = D'(\Sigma)$. In such case, firm i maximizes its profits π_i^T:

$$\max_{e_i, l_i} \pi_i^T = p\theta[\phi_i e_i]^\alpha l_i^\beta - wl_i - [z + \tau\gamma]\,e_i - F, \tag{14}$$

In line with the analysis above, individual output and profits under emission taxation are given by:

$$q_i^T = \left[p^{\alpha+\beta}\theta\beta^\beta w^{-\beta}\alpha^{\alpha}[z + \tau\gamma]^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}}, \tag{15}$$

$$\pi_i^T = [1-\alpha-\beta]\left[p\theta\phi_i^\alpha\beta^\beta w^{-\beta}\alpha^{\alpha}[z + \tau\gamma]^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}} - F. \tag{16}$$

Moreover, the cutoff value of the energy efficiency that satisfies the condition $\pi_0^T(\phi_0) = F$, which yields:

$$\phi_0^T = \left[\frac{F^{1-\alpha-\beta}[z + \tau\gamma]^\alpha w^\beta}{p\theta\beta^\beta\alpha^\alpha[1-\alpha-\beta]^{1-\alpha-\beta}}\right]^{\frac{1}{\alpha}}. \tag{17}$$

By simple inspection of Eqs. (13) and (17), it is easy to see when the tax equals the marginal damage of aggregate emissions, it holds that $\phi_0^T = \phi_0^{FB}$. Furthermore, by simple inspection of Eqs. (10) and (17), it is easy to see that $\phi_0^T > \phi_0^{NR}$. Before the imposition of the regulation, firms whose energy efficiency was lower than ϕ_0^T earned positive profits, but they did not take the social externality cost into consideration. The tax on emissions corrects the divergence between private and social incentives by forcing firms whose energy efficiency is in the range $[\phi_0^{NR}, \phi_0^T$ out of business and inducing those firms which do participate to choose an optimal level of production.[2]

3.2. Emission taxes

We can compute aggregate emissions and output under taxes (Σ^T, Q^T) by integrating individual emissions and output over the range $\left[\phi_0^T, \bar{\phi}\right]$, which leads to:

$$\Sigma^T = \gamma k_2 \int_{\phi_0^T}^{\bar{\phi}} \phi_i^{\frac{\alpha}{1-\alpha-\beta}}\, d\phi = \frac{\gamma k_2}{h}\left[\bar{\phi}^h - \left[\phi_0^T\right]^h\right]. \tag{18}$$

$$Q^T = \frac{[z + \tau\gamma]\,\Sigma^T}{p\alpha\gamma}, \tag{19}$$

where $k_2 = \left[p\theta\beta^\beta w^{-\beta}\alpha^{1-\beta}[z+\tau\gamma]^{-[1-\beta]}\right]^{\frac{1}{1-\alpha-\beta}}$.

Thus, the average emission intensity in the industry corresponds to $\frac{\Sigma^T}{Q^T} = \frac{p\alpha\gamma}{z+\tau\gamma}$. Dividing individual emissions γe_i^T by individual output q_i^T, we can see that individual emission intensity also corresponds to $\frac{p\alpha\gamma}{z+\tau\gamma}$. Note that with regard to the situation with no regulation, the average emission intensity of the industry is decreased under taxes. Moreover, like in the case with no regulation, the emission intensity of each firm in the industry is the same at the margin and given by the price ratio of output to emissions.

Let $\delta_i^T = \pi_i^{NR} - \pi_i^T > 0$ represent the gap in profits under emissions taxation vis-a-vis no regulation. Substracting Eq. (16) from Eq. (9), it is easy to show that δ_i^T is given by:

$$\delta_i^T = [1-\alpha-\beta]\left[p\theta\beta^\beta w^{-\beta}\alpha^\alpha\right]^{\frac{1}{1-\alpha-\beta}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}}\left[z^{\frac{-\alpha}{1-\alpha-\beta}} - [z+\tau\gamma]^{\frac{-\alpha}{1-\alpha-\beta}}\right]. \tag{20}$$

Moreover, let $\Delta\pi_i^T = \frac{\delta_i^T}{\pi_i^{NR}} > 0$ represent the percentage reduction in firm i' s profits under emissions taxation vis-a-vis no regulation. To study the incidence of the regulatory costs of environmental taxation across firm size, we compute the first and second order derivative of $\Delta\pi_i^T$ with regard to ϕ_i, which leads to the following proposition:

Proposition 1. *Emission taxes reduce by a larger percentage profits for smaller firms than for larger firms.*

Proof. Substituting Eq. (20) in $\Delta\pi_i^T$ and differentiating with respect to ϕ_i yields:

$$\frac{\partial\Delta\pi_i^T}{\partial\phi_i} = \underbrace{-\left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{F}{\phi_i}\frac{\Delta\pi_i^T}{\pi_i^{NR}}}_{Economies\ of\ Scale} < 0$$

$$\frac{\partial^2\Delta\pi_i^T}{(\partial\phi_i)^2} = \left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\frac{F\Delta\pi_i^T}{\phi_i^2\pi_i^{NR}} + \frac{F\Delta\pi_i^T}{\phi_i[\pi_i^{NR}]^2}\frac{\partial\pi_i^{NR}}{\partial\phi_i} - \frac{F}{\phi_i\pi_i^{NR}}\frac{\partial\Delta\pi_i^T}{\partial\phi_i}\right] > 0.$$

Hence, $\Delta\pi_i^T$ decreases at decreasing rate as ϕ_i increases, implying that in relative terms, emission taxes increase the cost of compliance (and thus reduce the profits) of the smaller firms more than they reduce the profits of larger firms. The intuition behind this result is the existence of economies of scale. As mentioned before, under emission

[2] This result is consistent with Spulber (1985). A recent paper by Shinkuma and Sugeta (2016) shows though that when firms face idiosyncratic ex-ante cost uncertainty, auctioned permits induce insufficient entry, while under a linear emission tax scheme,market entry can be either excessive or insufficient.

taxes the energy and emission intensity of each firm in the industry is the same at the margin. However, in absolute terms, large firms produce more output and release more emissions. The fixed cost F puts the smaller firms at a unit cost disadvantage; the normalized fixed cost $\frac{F}{\phi_i}$ reflects the fact that the percentage reduction in profits of the larger firms is smaller since they can spread the fixed cost across a larger output. The percentage reduction in profits decreases at a decreasing rate since the use of energy (and emission tax payments) is a concave function of the energy efficiency. ■

3.3. Emission standard

Under a uniform emission standard, the government restricts the individual emissions generated during the production process to the level $\bar{\xi}$. In our setting, this restriction is equivalent to a restriction on the use of the energy input. Thus, firm i maximizes profits given by the constraint $\xi_i \le \bar{\xi}$, or:

$$\max_{e_i,l_i} \pi_i^S = p\theta[\phi_i e_i]^\alpha l_i^\beta - wl_i - ze_i - F \qquad s.t. \;\; e_i \le \bar{\xi}\gamma^{-1}. \tag{21}$$

Since the standard is uniform and firms are heterogenous, we should expect it to be binding only for some firms. Taking the case without regulation as the baseline, we should expect the standard to be binding if $\xi_i^{NR} \ge \bar{\xi}$. If the standard is *not* binding, the choice of inputs proceeds as in the case without regulation. If the standard *is* binding, the FOC wrt l_i is:

$$l_i^S = \left[\frac{p\theta\beta\phi\bar{\xi}^\alpha\gamma^{-\alpha}}{w}\right]^{\frac{1}{1-\beta}}, \tag{22}$$

while the energy to labor ratio is equal to:

$$\frac{e_i^S}{l_i^S} = \left[\frac{\left[\bar{\xi}\gamma^{-1}\right]^{1-\alpha-\beta} w}{p\theta\beta\phi_i^\alpha}\right]^{\frac{1}{1-\beta}}. \tag{23}$$

Substituting l_i^S and e_i^S in Eqs. (1) and (21) yields to output and profits for those firms for which the standard is binding:

$$q_i^S = \left[p^\beta\beta^\beta w^{-\beta}\theta\right]^{\frac{1}{1-\beta}}\left[\bar{\xi}\gamma^{-1}\right]^{\frac{\alpha}{1-\beta}}\phi_i^{\frac{\alpha}{1-\beta}}. \tag{24}$$

$$\pi_i^S = [1-\beta]\left[p\theta\beta^\beta\phi_i^\alpha\left[\bar{\xi}\gamma^{-1}\right]^\alpha w^{-\beta}\right]^{\frac{1}{1-\beta}} - z\left[\bar{\xi}\gamma^{-1}\right] - F. \tag{25}$$

In order to compare environmental policies, we assume that the regulatory goal both under standards and taxes has an equivalent effect on the reduction of aggregate emissions. In other words, the introduction of an emission standard is designed so as to reduce emissions to some level $\bar{E} = \Sigma^T$. Therefore, we can solve for $\bar{\xi}$ by integrating emissions over the range $\left[\phi_0^{NR}, \bar{\phi}\right]$ and equalizing this to Σ^T in Eq. (18). As explained above, the emission standard is expected to be binding for some marginal firm with $\phi_i = \hat{\phi}_1 > \phi_0^{NR}$. This implies that smaller firms will keep generating emissions equal to ξ_i^{NR} while firms with $\phi_i > \hat{\phi}_1$ will generate $\bar{\xi}$, which leads to the following condition:

$$\int_{\phi_0^{NR}}^{\hat{\phi}_1} \xi_i^{NR} d\phi + \int_{\hat{\phi}_1}^{\bar{\phi}} \bar{\xi} d\phi = \Sigma^T.$$

Therefore, the standard $\bar{\xi}$ can be represented as:

$$\bar{\xi} = \left[\frac{\Sigma^T - \frac{\gamma k_1}{h}\left[\left[\hat{\phi}_1\right]^h - \left[\phi_0^{NR}\right]^h\right]}{\bar{\phi} - \hat{\phi}_1}\right]. \tag{26}$$

Eq. (26) implies that a stricter optimal regulatory goal (lower aggregate emissions Σ^T) will require the implementation of a stricter standard $\bar{\xi}$. In turn, a stricter standard $\bar{\xi}$ will imply that a larger number of firms will be obliged to reduce their emissions to the level $\bar{\xi}$. Regarding the emission intensity, if $\phi_i \in \left[\phi_0^{NR}, \widehat{\phi}_1\right.$, the standard $\bar{\xi}$ is not binding and energy used and output are given by Eqs. (6) and (8), respectively. Therefore, the average (and individual) emission intensity in this interval is the same as in the case without regulation and equal to $\frac{p\alpha\gamma}{z}$. If $\phi_i \in \left[\widehat{\phi}_1, \bar{\phi}\right]$, the standard is binding and individual emissions are equal to $\bar{\xi}$. Dividing $\bar{\xi}$ by the output level in Eq. (24) leads to an individual emission intensity equal to $\gamma^{\frac{\alpha}{1-\beta}}\bar{\xi}^{\frac{1-\alpha-\beta}{1-\beta}}\left[p^\beta\beta^\beta w^{-\beta}\theta\phi_i^\alpha\right]^{\frac{-1}{1-\beta}}$. Note that unlike emission taxes, under emission standards the individual emission intensity depends on the energy efficiency parameter ϕ_i. It decreases as energy efficiency increases at a decreasing rate, implying that large firms use the input that generates emissions less intensively.

Let $\delta_i^S = \pi_i^{NR} - \pi_i^S > 0$ represent the gap in firm i's profits under emission standards vis-a-vis no regulation. Subtracting Eq. (25) from Eq. (9), it is easy to show that if $\phi_i > \widehat{\phi}_1$, δ_i^S is given by:

$$\begin{aligned}\delta_i^S \;=\; &[1-\alpha-\beta]\left[p\theta\beta^\beta w^{-\beta}\alpha^\alpha z^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}} \\ &-[1-\beta]\left[p\theta\beta^\beta\phi_i^\alpha\left[\bar{\xi}\gamma^{-1}\right]^\alpha w^{-\beta}\right]^{\frac{1}{1-\beta}} + z\left[\bar{\xi}\gamma^{-1}\right].\end{aligned} \tag{27}$$

Moreover, let $\Delta\pi_i^S = \frac{\delta_i^S}{\pi_i^{NR}} > 0$ represent the percentage reduction in firm i' s profits under emission standards vis-a-vis no regulation. To study the incidence of the regulatory costs of emission standards across firm size, we compute the first and second order derivative of $\Delta\pi_i^S$ with regard to ϕ_i, which leads to the following proposition:

Proposition 2. *Emission standards reduce by a larger percentage profits for larger firms than for smaller firms.*

Proof. Substituting Eq. (27) in $\Delta\pi_i^S$ and differentiating with respect to ϕ_i yields

$$\begin{aligned}\frac{\partial\Delta\pi_i^S}{\partial\phi_i} \;=\; &\underbrace{\left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\frac{\alpha\left[p\theta\beta^\beta\phi_i^\alpha\left[\bar{\xi}\gamma^{-1}\right]^\alpha w^{-\beta}\right]^{\frac{1}{1-\beta}} - z\left[\bar{\xi}\gamma^{-1}\right]}{\phi_i\pi_i^{NR}}\right]}_{\text{Regulatory assymmetry}} \\ &\underbrace{-\left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{F}{\phi_i}\frac{\Delta\pi_i^S}{\pi_i^{NR}}}_{\text{Economies of scale}} > 0.\end{aligned} \tag{28}$$

Hence, the incidence of the regulatory costs of emission standards across firm size depends on two counteracting effects. The first effect - regulatory asymmetry (RA) - is positive and captures the fact that emission standards distort the emission intensity of larger firms the most. Compared with nonregulation (where emission intensity is the same across firms), under emission standards the larger firms are forced to use the energy input less intensively. Thus, their profits are reduced by a larger percentage than those of smaller firms.

Like in the case of taxation, the second effect, the scale effect (SE), is negative and captures the fact that the fixed cost F puts the smaller firms at a unit cost disadvantage, and hence, vis-a-vis no regulation, the profits of the smaller firms are reduced to a larger extent than those of larger firms. ■

We can show that the regulatory asymmetry effect is larger than the scale effect implying that profits under emission standards are reduced by a larger percentage for larger firms than for smaller firms (see Appendix A). Moreover, differentiating $\frac{\partial \Delta\pi_i^S}{\partial \phi_i}$ with respect to ϕ_i yields:

$$\frac{\partial^2 \Delta\pi_i^S}{(\partial \phi_i)^2} = \left[\frac{\partial RA}{\partial \phi_i} + \frac{\partial SE}{\partial \phi_i}\right].$$

As in the case of taxes we can show that $\frac{\partial SE}{\partial \phi_i} > 0$. Hence, the scale effect decreases at a decreasing rate since the use of energy is a concave function of the energy efficiency. The derivative $\frac{\partial RA}{\partial \phi_i}$ is given by:

$$\frac{\partial RA}{\partial \phi_i} = -\left[\frac{1-\alpha-\beta}{1-\beta}\right]\frac{RA}{\phi_i} - \frac{RA}{\pi_i^{NR}}\frac{\partial \pi_i^{NR}}{\partial \phi_i} + \left[\frac{\alpha^2}{[1-\alpha-\beta][1-\beta]}\right]\left[\frac{z\left[\bar{\xi}\gamma^{-1}\right]}{\phi_i^2 \pi_i^{NR}}\right] < 0.$$

That is, if $\phi_i > \widehat{\phi}_1$, the regulatory asymmetry effect increases at an increasing rate as ϕ_i increases. Since the first part of the $\frac{\partial^2 \Delta\pi_i^S}{(\partial \phi_i)^2}$ is negative and the second part is positive, the sign of the $\frac{\partial^2 \Delta\pi_i^S}{(\partial \phi_i)^2}$ is ambiguous.

3.4. Performance standard

Under a performance standard, emission intensity is fixed by policy at $\frac{\xi_i}{q_i} \leq \kappa$. Firms can meet partly this restriction by reducing emissions in the numerator and partly by increasing output in the denominator. In our setting, this restriction is equivalent to a restriction on the use of input energy equal to $e_i \leq \kappa\gamma^{-1} q_i$. Thus, firm i maximizes

$$\max_{e_i, l_i} \pi_i^{PS} = p\theta(\phi_i e_i)^\alpha l_i^\beta - w l_i - z e_i - F \qquad \text{s.t.} \quad e_i \leq \kappa\gamma^{-1} q_i.$$

If the constraint is binding, the choice of the energy input is given by:

$$e_i = \kappa\gamma^{-1}\theta(\phi_i e_i)^\alpha l_i^\beta$$

or:

$$e_i^{PS} = \left[\kappa\gamma^{-1}\theta\phi_i^\alpha l_i^\beta\right]^{\frac{1}{1-\alpha}}, \tag{29}$$

and the profit maximization problem becomes:

$$\max_{l_i} \pi_i^{PS} = p\theta\left(\phi_i e_i^{PS}\right)^\alpha l_i^\beta - w l_i - z e_i^{PS} - F. \tag{30}$$

Substituting Eq. (29) into Eq. (30) and solving the FOC wrt l_i yields:

$$l_i^{PS} = \left[\frac{\kappa\gamma^{-1}\theta\beta^{1-\alpha}\left[p\kappa^{-1}\gamma - z\right]^{1-\alpha}}{[1-\alpha]^{1-\alpha} w^{1-\alpha}}\phi_i^\alpha\right]^{\frac{1}{1-\alpha-\beta}}. \tag{31}$$

Substituting Eq. (31) into Eq. (29), we solve for e_i^{PS} as:

$$e_i^{PS} = \left[\frac{\kappa\gamma^{-1}\theta\beta^\beta\left[p\kappa^{-1}\gamma - z\right]^\beta \phi_i^\alpha}{[1-\alpha]^\beta w^\beta}\right]^{\frac{1}{1-\alpha-\beta}}, \tag{32}$$

where

$$\frac{e_i^{PS}}{l_i^{PS}} = \frac{[1-\alpha]\,w}{\beta\left[p\kappa^{-1}\gamma - z\right]}. \tag{33}$$

Finally, substituting l_i^{PS} and e_i^{PS} in Eq. (30) yields:

$$\pi_i^{PS} = [1-\alpha-\beta]\left[\kappa\gamma^{-1}\theta\left[\frac{p\kappa^{-1}\gamma - z}{1-\alpha}\right]^{1-\alpha}\phi_i^\alpha\beta^\beta w^{-\beta}\right]^{\frac{1}{1-\alpha-\beta}} - F. \tag{34}$$

Following our initial regulatory goal, i.e. the ex-post equivalence of aggregate emissions, the stringency of the performance standard is set so as to produce aggregate emissions equal to $\bar{E} = \Sigma^T$. Assuming that this aggregate emission level is obtained with an emission intensity equal to κ and solving for the cutoff value ϕ_0^{PS} that satisfies the condition $\pi_0^{PS}\left(\phi_0^{PS}\right) = F$ yields:

$$\phi_0^{PS} = \left[\frac{F^{1-\alpha-\beta}[1-\alpha]^{1-\alpha} w^\beta \gamma}{\kappa\theta\beta^\beta\left[p\kappa^{-1}\gamma - z\right]^{1-\alpha}[1-\alpha-\beta]^{1-\alpha-\beta}}\right]^{\frac{1}{\alpha}}. \tag{35}$$

As usual, aggregate emissions under performance standard Σ^{PS} are calculated by integrating individual emissions ξ_i^{PS} over the range $\left[\phi_0^{PS}, \bar{\phi}\right]$, which leads to:

$$\Sigma^{PS} = \frac{1}{h}\left[\frac{\kappa\gamma^{-1}\left[p\kappa^{-1}\gamma - z\right]^\beta}{[1-\alpha]^\beta}\right]^{\frac{1}{1-\alpha-\beta}}\left[\bar{\phi}^h - \left[\phi_0^{PS}\right]^h\right]. \tag{36}$$

Let $\delta_i^{PS} = \pi_i^{NR} - \pi_i^{PS} > 0$ represent the gap in profits under performance standards vis-a-vis no regulation. Subtracting Eq. (34) from Eq. (9), it is easy to show that δ_i^{PS} is given by:

$$\delta_i^{PS} = [1-\alpha-\beta]\left[\theta\beta^\beta w^{-\beta}\right]^{\frac{1}{1-\alpha-\beta}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}} \times \left[\left[p\alpha^\alpha z^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}} - \left[\left[\kappa\gamma^{-1}\left[\frac{p\kappa^{-1}\gamma - z}{1-\alpha}\right]^{1-\alpha}\right]\right]^{\frac{1}{1-\alpha-\beta}}\right]. \tag{37}$$

Moreover, let $\Delta\pi_i^{PS} = \frac{\delta_i^{PS}}{\pi_i^{NR}} > 0$ represent the percentage reduction in firm i's profits under performance standards vis-a-vis no regulation. To study the incidence of the regulatory costs of emission standards across firm size, we compute the first and second order derivative of $\Delta\pi_i^{PS}$ with regard to ϕ_i, which leads to the following proposition:

Proposition 3. *Performance standards reduce by a larger percentage profits for smaller firms than for larger firms.*

Proof. Substituting Eq. (37) in $\Delta\pi_i^{PS}$ and differentiating with respect to ϕ_i yields:

$$\frac{\partial\Delta\pi_i^{PS}}{\partial\phi_i} = -\underbrace{\left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{F}{\phi_i}\frac{\Delta\pi_i^{PS}}{\pi_i^{NR}}}_{Economies\ of\ Scale} < 0,$$

$$\frac{\partial^2\Delta\pi^{PS}}{(\partial\phi_i)^2} = \left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\frac{F\Delta\pi_i^{PS}}{\phi_i^2\pi_i^{NR}} + \frac{F\Delta\pi_i^{PS}}{\phi_i\left[\pi_i^{NR}\right]^2}\frac{\partial\pi_i^{NR}}{\partial\phi_i} - \frac{F}{\phi_i\pi_i^{NR}}\frac{\partial\Delta\pi_i^{PS}}{\partial\phi_i}\right] > 0.$$

Like the case of emission taxes, $\Delta\pi_i^{PS}$ decreases at a decreasing rate as ϕ_i increases, implying that in relative terms, performance standards increase the cost of compliance (and thus reduce the profits) of the larger firms to a lower extent. As in the case of emission taxes, the emission intensity of each firm in the industry is the same at the margin and given by the regulation. The regressive incidence of performance standards is explained by the existence of economies of scale. This effect decreases at a decreasing rate since the use of energy is a concave function of the energy efficiency. ■

Proposition 4. *Emission taxes reduce the profits of larger firms by a larger percentage than do performance standards.*

Proof. The condition $\left|\frac{\partial\Delta\pi_i^T}{\partial\phi_i}\right| > \left|\frac{\partial\Delta\pi_i^{PS}}{\partial\phi_i}\right|$ holds if $\pi_i^T - \pi_i^{PS} < 0$. In Appendix B we prove that $\pi_i^T - \pi_i^{PS}$ is always negative, meaning that $\pi_i^T < \pi_i^{PS}$. Hence, and not surprisingly, emission taxes reduce firm profits by larger percentage. As pointed out by Fullerton and Heutel (2010) a restriction on emissions per unit of output is equivalent to a combination of a tax on emissions and subsidy to output. The actual cost of the regulation is larger under emission taxes since firms must pay the tax for each unit of emissions they release. Instead, under performance standards, firms are granted κq_i^{PS} units of emission free of charge. The higher the level of output q_i^{PS}, the larger the amount of emissions granted free of charge. Hence, as ϕ_i increases, and so does output, the actual cost of the regulation under performance standard decreases, implying that vis-a-vis taxation performance standards reduce the profits of larger firms by a lower percentage than do emission taxes. ■

Proposition 5. *We have the following ranking regarding how environmental policies modify the optimal scale of firms.*

(a) The minimum optimal firm size is larger under emission taxes and performance standards than under no regulation. Further, the minimum optimal firm size is larger under emission taxes than under performance standards, i.e., $\phi_0^{NR} < \phi_0^{PS} < \phi_0^T$.
(b) There is a critical threshold $\widehat{\phi}_1$ that defines whether emission standards are binding. Since $\widehat{\phi}_1 > \phi_0^{NR}$, it follows that emission standards do not affect the minimum optimal firm size.

Proof.

(a) In Appendix B we provide a formal proof for this unique equilibrium, $\phi_0^{NR} < \phi_0^{PS} < \phi_0^T$ and we show that no other ranking can arise as an equilibrium outcome. Notice also that since emission taxes reduce individual firm profits by a larger percentage, the marginal firm in the case of taxation should be more energy efficient than the corresponding one in the case of performance standards.
(b) $\widehat{\phi}_1$ is always higher than ϕ_0^{NR}, provided that $\bar{\xi} > \xi_0^{NR}$ meaning that the emission standard is higher than the individual emissions generated by the smallest active firm in the case of non-regulation. This is a realistic assumption since emission standards - when they are in place - are not binding for the whole distribution of active firms. A very stringent emission standard $\bar{\xi}$ would be comparable with unrealistically high per unit tax or unrealistically low performance standard, which would all significantly reduce the level of production. ■

4. The choice of policy instruments and the distribution of factors

To analyze the effects of the choice of policy instruments on the distribution of factors, we model the choice between two technologies. In particular, technology 1 (T_1) increases the technology index from θ to $\hat{\theta}$, while technology 2 (T_2) reduces the generation of emissions per unit of energy from γ to $\tilde{\gamma}$.

From the analysis above, recall that if the regulations are binding, individual emissions, the energy to labor ratio and individual emission intensity under emission taxes (T), emission standards (S) and performance standard (PS) correspond to: (Table 1)

Hence, under taxes and performance standards, individual emissions increase when θ increases. However, the firms' relative use of inputs and emission intensity do not depend on θ. In contrast, under emission standards the firms' relative use of energy and emission intensity are reduced if θ increases. θ has no effect on individual emissions if the standard is binding.

Under taxes and emission standards, T_2 increases the firms' relative use of energy while reducing the emission intensity (as well as individual emissions in the case of taxes). Finally, under performance standards, T_2 increases individual emissions and the firms' relative use of energy but has no effect on the emission intensity, which is fixed by the regulation. However, if the adoption of T_2 makes the standard κ non-binding, the emission intensity is reduced to $\frac{p\alpha\tilde{\gamma}}{z}$ and the energy to labor ratio is increased to $\frac{\alpha w}{\beta z}$.

All in all, the technologies affect individual emissions, the relative use of inputs, and emission intensity differently depending on the policy instrument in place. However, for simplicity, let us refer to T_1 as a neutral technical change (which holds for all cases but the emission standards) and T_2 as an emission-saving technological change. Without loss of generality, we assume that both options have the same investment cost G, and normalize γ to 1 and hence $\tilde{\gamma} < 1$. We

Table 1
Individual emissions, energy/labor ratio and emission intensity.

	Individual emissions	Energy/labor	Emission intensity
T	$\gamma\left[\frac{p\theta\beta^\beta w^{-\beta}\alpha^{1-\beta}\phi_i^\alpha}{[z+\tau\gamma]^{[1-\beta]}}\right]^{\frac{1}{1-\alpha-\beta}}$	$\frac{\alpha w}{\beta[z+\tau\gamma]}$	$\frac{p\alpha\gamma}{z+\tau\gamma}$
S	$\bar{\xi}$	$\left[\frac{\bar{\xi}}{\gamma}\right]^{\frac{1-\alpha-\beta}{1-\beta}}\left[p\theta\beta w^{-1}\phi_i^\alpha\right]^{\frac{-1}{1-\beta}}$	$\gamma^{\frac{\alpha}{1-\beta}}\bar{\xi}^{\frac{1-\alpha-\beta}{1-\beta}}\left[p^\beta\theta\beta^\beta w^{-\beta}\phi_i^\alpha\right]^{\frac{-1}{1-\beta}}$
PS	$\left[\frac{\kappa\gamma^{-1}\theta\beta^\beta\left[p\kappa^{-1}\gamma-z\right]^\beta\phi_i^\alpha}{[1-\alpha]^\beta w^\beta}\right]^{\frac{1}{1-\alpha-\beta}}$	$\frac{[1-\alpha]w}{\beta\left[p\kappa^{-1}\gamma-z\right]}$	κ

also assume that both technologies are profitable and focus instead on the choice of technology to understand how the distribution of factors is affected by the choice of different environmental policies.

4.1. Emission taxes

Let $\Gamma_i^T(\hat{\theta},\theta)$ represent firm i's profits from adoption of T_1. Using Eq. (16), $\Gamma_i^T(\hat{\theta},\theta)$ can be represented as:

$$\Gamma_i^T(\hat{\theta},\theta)=[1-\alpha-\beta]\left[p\phi_i^\alpha\beta^\beta w^{-\beta}\alpha^\alpha[z+\tau]^{-\alpha}\right]^{\frac{1}{1-\alpha-\beta}}\left[\hat{\theta}^{\frac{1}{1-\alpha-\beta}}-\theta^{\frac{1}{1-\alpha-\beta}}\right]-\Lambda.$$

Profits from adoption of T_2 can be represented as $\Gamma_i^T(\tilde{\gamma},1)$:

$$\Gamma_i^T(\tilde{\gamma},1)=[1-\alpha-\beta]\left[p\theta\phi_i^\alpha\beta^\beta w^{-\beta}\alpha^\alpha\right]^{\frac{1}{1-\alpha-\beta}}\left[[z+\tau\tilde{\gamma}]^{\frac{-\alpha}{1-\alpha-\beta}}-[z+\tau]^{\frac{-\alpha}{1-\alpha-\beta}}\right]-\Lambda,$$

where $\Lambda = G - F > 0$.

From these equations we can show that T_1 is most profitable when the technology index $\widehat{\theta}$ exceeds a critical threshold given by $\theta_T^* = \left[\frac{z+\tau}{z+\tau\tilde{\gamma}}\right]^\alpha\theta$. For $\hat{\theta}=\theta_T^*$, both technologies are equally profitable, while T_2 is more profitable if $\hat{\theta}<\theta_T^*$.

4.2. Emission standards

From Eq. (25) we can see that if the standard is binding, the profits from adopting T_1 can be represented as:

$$\Gamma_i^S(\hat{\theta},\theta)=\left[1-\beta^{\frac{1}{1-\beta}}\right]\left[p\phi_i^\alpha\left[\bar{\xi}\gamma^{-1}\right]^\alpha w^{-\beta}\right]^{\frac{1}{1-\beta}}\left[\hat{\theta}^{\frac{1}{1-\beta}}-\theta^{\frac{1}{1-\beta}}\right]-\Lambda.$$

Profits from adopting T_2 can be represented as:

$$\Gamma_i^S(\tilde{\gamma},1)=\left[1-\beta^{\frac{1}{1-\beta}}\right]\left[p\theta\phi_i^\alpha\left[\bar{\xi}\gamma^{-1}\right]^\alpha w^{-\beta}\right]^{\frac{1}{1-\beta}}\left[\tilde{\gamma}^{\frac{-\alpha}{1-\beta}}-1\right]-\Lambda.$$

Like in the previous case, there is critical threshold $\theta_S^*=\tilde{\gamma}^{-\alpha}\theta$ that defines which technology is the most profitable. T_1 is more profitable than T_2 when $\hat{\theta}>\theta_S^*$, while the reverse holds for $\hat{\theta}<\theta_S^*$. For $\hat{\theta}=\theta_S^*$, both technologies are equally profitable.

4.3. Performance standards

Finally, from Eq. (34) we can see that the profits from adoption of T_1 can be represented as:

$$\Gamma_i^{PS}(\hat{\theta},\theta) = [1-\alpha-\beta]\left[\kappa\left[\frac{p\kappa^{-1}-z}{1-\alpha}\right]^{1-\alpha}\phi_i^\alpha\beta^\beta w^{-\beta}\right]^{\frac{1}{1-\alpha-\beta}} \times\left[\hat{\theta}^{\frac{1}{1-\alpha-\beta}}-\theta^{\frac{1}{1-\alpha-\beta}}\right]-\Lambda.$$

Profits from adoption of T_2 can be represented as:

$$\Gamma_i^{PS}(\tilde{\gamma},1) = [1-\alpha-\beta]\left[\frac{\theta\phi_i^\alpha\beta^\beta w^{-\beta}\kappa}{[1-\alpha]^{1-\alpha}}\right]^{\frac{1}{1-\alpha-\beta}} \times\left[\left[\tilde{\gamma}^{-1}\left[p\kappa^{-1}\tilde{\gamma}-z\right]^{1-\alpha}\right]^{\frac{1}{1-\alpha-\beta}}-\left[\left[p\kappa^{-1}-z\right]^{1-\alpha}\right]^{\frac{1}{1-\alpha-\beta}}\right]-\Lambda.$$

Again, there is a critical threshold $\theta_{PS}^* = \theta\tilde{\gamma}^{-1}\left[\frac{p\kappa^{-1}\tilde{\gamma}-z}{p\kappa^{-1}-z}\right]^{1-\alpha}$ that defines which technology is the most profitable. Investment in T_1 is more profitable than T_2 when $\hat{\theta}>\theta_{PS}^*$, while the reverse holds for $\hat{\theta}<\theta_{PS}^*$. For $\hat{\theta}=\theta_{PS}^*$, both technologies are equally profitable.

Proposition 6. *Compared with neutral technological change, the profitability of emission-saving technological change is the highest under emission standards, followed by emission taxes and performance standards.*

Proof. Comparing the thresholds, we show in Appendix C that for $\tilde{\gamma}<1$:
$\theta_S^*>\theta_T^*$, $\theta_S^*>\theta_{PS}^*$ and $\theta_T^*>\theta_{PS}^*$.
Hence, it follows that $\theta_S^*>\theta_T^*>\theta_{PS}^*$. ■

Table 2 sheds more light on the incentives of firms for adopting new technologies depending on the policy instrument enforced.

This result is interesting. As discussed above, emission standards distort the choice of inputs the most, affecting quite significantly the profits of those firms for which the standard is binding. T_2 allows firms to increase the use of the energy input, reducing the shadow cost of the regulation. The finding that T_2 is most likely to be adopted under emission standards goes against previous studies suggesting that market-based instruments create more effective technology adoption incentives than conventional regulatory standards (see Requate, 2005 for a survey). This result relies on the logic that under emission standards, the incentive for adoption is given by the increased profits resulting from using new technology when firms are restricted to emit no more than $\bar{\xi}$. In comparison, under market-based instruments, firms would instead increase their emission reductions even further to reduce tax payments. Our analysis shows, however, that when the regulatory asymmetries created by emission standards are taken into account, the profitability of emission-saving-biased technological change is higher under emission standards than under market-based instruments. The most productive firms are more likely to invest in new technology. Under emission standards those are the firms that face the larger percentage reduction in profits due to the regulation, and hence benefit the most from investing in T_2.

Finally, the finding that adoption of T_2 is more likely under emission taxes than under performance standard is in line with Proposition 4. For equivalent stringencies of these policy instruments, firms face a larger percentage reduction in profits under emission taxes, which creates incentives to invest in technologies that reduce the cost of the regulation. It is worth mentioning that a similar argument has been advanced in the empirical studies by Klemetsen et al. (2016) and Bye and Klemetsen (2018). They argue that emission standards can spur innovations since firms respond strongly to prohibitions that involve a limit on the production activity and emission standards send transparent signals to firms, reducing the risk of new technology investments. Furthermore, in their analysis of alternative policy instruments on environmental performance, Bye and Klemetsen (2018) find that emission standards promote persistent effects on

Table 2
Adoption of alternative technologies under T, S and PS.

θ	θ_{PS}^*	θ_T^*	θ_S^*
T	T_2^T		T_1^T
S	T_2^S		T_1^S
PS	T_2^{PS}	T_1^{PS}	

environmental performance. In contrast, emission taxes will only have potential persistent effects if environmental taxes are increasing over time.

5. Numerical example

In this section we present a numerical example of the size distribution induced by the different policies under analysis. This example is only used for illustrative purposes, is robust in parameter changes and the results are in line with the theoretical predictions of our model. In Table 3, we provide values for some of our key parameters and calculate the resulting choice of inputs, profits, and aggregate emissions and output.

The production elasticity of emissions and labor is set at $\alpha = 0.2$ and $\beta = 0.5$, respectively. The general productivity parameter, θ, is equal to 2 and the fixed entry cost of firms is $F = 21$. The price of the output is set at $p = 5$, while the wages and the price of energy are set at $w = 1$ and $z = 1.6$, respectively. As discussed in Section 2, the optimal emission tax corresponds to the marginal damage of aggregate emissions. For simplicity, we assume that the marginal damage is linear and hence the optimal tax is given by $\tau = b\Sigma^{FB}$. Using the parameter values of Table 3, we solve for the first best level of aggregate emissions generated by the active firms as $\Sigma^{FB} = 465$, which corresponds to a 20% reduction on aggregate emissions. Hence, the optimal tax per unit of emissions is equal to $\tau = 0.2$. Finally, we assume that the initial number of firms is $N = 50$, and that the energy efficiency parameter of these firms is uniformly distributed in the interval 0, 1]. This is to say, the lower bound of the distribution is given by $\underline{\phi} \simeq 0$ and the upper bound of the distribution is given by $\bar{\phi} = 1$.

Using the parameter values presented in Table 3, we compute the size distribution of firms under different environmental regulations. Table 4 summarizes the main results. In the case without regulation, 12 out of 50 firms cannot operate since they are not profitable enough. Firms with energy efficiency lower than $\phi = 0.26$ are not profitable even in the case of no regulation.

Firms need to be more energy efficient in order to stay in the market if optimal environmental taxes are imposed. The cutoff value in this specific numerical example is 0.3. Hence, the internalization of the cost of emissions made firms in the interval $[0.26, 0.3)$ exit the market. The case of standards is different. For the firms with energy efficiency in the range $[0.26, 0.5)$, the emissions standard is not binding. Those firms for which the standard is binding, i.e., $\phi_i \in [0.5, 1]$, produce less than before since they are restricted in the use of the energy (or equivalently in the generation of emissions), as illustrated in Fig. 1. Finally, the cutoff value in the case of performance standards is equal to 0.28, which implies that firms in the interval $[0.28, 0.3)$ will still find it profitable to operate under performance standards but not under taxes.

When it comes to output, it is clear from Table 4 that output is higher under both performance and emission standards than under taxation, which is easily explained if we take into account that firms pay taxes for the total emissions they generate, while in the case of standards firms are granted a certain number of emissions free of charge. Despite the fact that for many firms the emission standard is not binding, the total output under this policy is reduced significantly relative to the case of non-regulation since the larger firms that used to produce a lot are now restricted by the emission standard. Thus, we can rank the total output under the four regimes as $Q^{NR} > Q^{PS} > Q^{S} > Q^{*}$.

Table 4
Numerical results.

	ϕ_0	$\widehat{\phi}_1$	Σ	Q	Σ/Q	W	$\hat{\theta}$
Non-regulation	0.26		584	934	0.63	529	
Emission tax (*First best*)	0.3		465	837	0.56	546	2.009
Emission standard	0.26	0.5	465	859	0.54	537	2.091
Performance standard	0.28		465	877	0.53	542	2.005

As expected, aggregate emissions were reduced to the optimal level of emissions in all cases (as we set the stringency of the policies so they produce equivalent aggregate emissions ex-post). In terms of our numerical example this corresponds to a 20% decrease in the level of emissions (with regards to non-regulation). Table 4 also shows the average emissions-output ratio. We can see that - in line with our analytical results - the average emission intensity is the lowest under performance standards, followed by emission standards and then taxes. $(\Sigma/Q)^{PS} < (\Sigma/Q)^{S} < (\Sigma/Q)^{T}$. When it comes to output, emission taxes lead to the largest reduction since it is the only policy that imposes a real cost on firms for each unit of emissions they release.

When it comes to welfare effects, Table 4 provides the values of welfare (i.e., aggregate profits of active firms minus the environmental damages) under the different policy instruments. In calculating our indicator in the case of the optimal taxes, we sum back aggregate tax payments as they only represent a transfer between firms and the government. This is to say, they should not be considered as a reduction in aggregate profits. Further, the aggregate profits and the corresponding environmental damages in the case of emission standards correspond to the weighted average of the profits and environmental damages of those firms for which the standard is not binding and those for which the standard is binding. Two factors determine the observed differences in the welfare levels: (i) the cost of compliance of the different environmental policies and (ii) the different number of firms exiting the market after the implementation of each environmental policy. Our numerical example provides the following ranking: $W^{*} > W^{PS} > W^{S} > W^{NR}$. As expected, the optimal tax leads to a higher welfare level compared to the rest of the policies. The ranking for the rest of the three cases studied in this paper is as follows: performance standards lead to higher welfare, followed by emission standards and non-regulation. The fact that emission standards lead to lower welfare is interesting since firms are not required to pay for their emissions in this case. However, the fact that the regulation significantly affects the choice of inputs and restricts firms with the highest energy efficiency implies that this policy has the most negative effects on aggregate profits, though it impacts small firms to a lower extent. The environmental damage is the largest in the case of non-regulation, and not surprisingly, any kind of environmental policy will lead to higher welfare levels compared to the case where no measures are taken.

In order to illustrate Propositions 1, 2, and 3, we calculate the percentage gap in profits under each policy instrument vis-a-vis no regulation, i.e., $\Delta\pi_i^j = \frac{\pi_i^{NR} - \pi_i^j}{\pi_i^{NR}}, \vee j = T, S, PS$. As we can see in Fig. 2, in relative terms, emission standards are much more stringent for larger firms than for smaller firms. As expected, taxes and performance standards impose a higher cost to smaller firms. Moreover, under performance standards large firms lose a smaller part of their profits (vis-a-vis no regulation) than under optimal taxes. As

Table 3
Parameter values.

α	β	θ	p	w	z	τ	F	γ	$\tilde{\gamma}$	b	N	$\bar{\phi}$	$\underline{\phi}$
0.2	0.5	2	5	1	1.6	0.2	21	1	0.8	0.00043	50	1	0

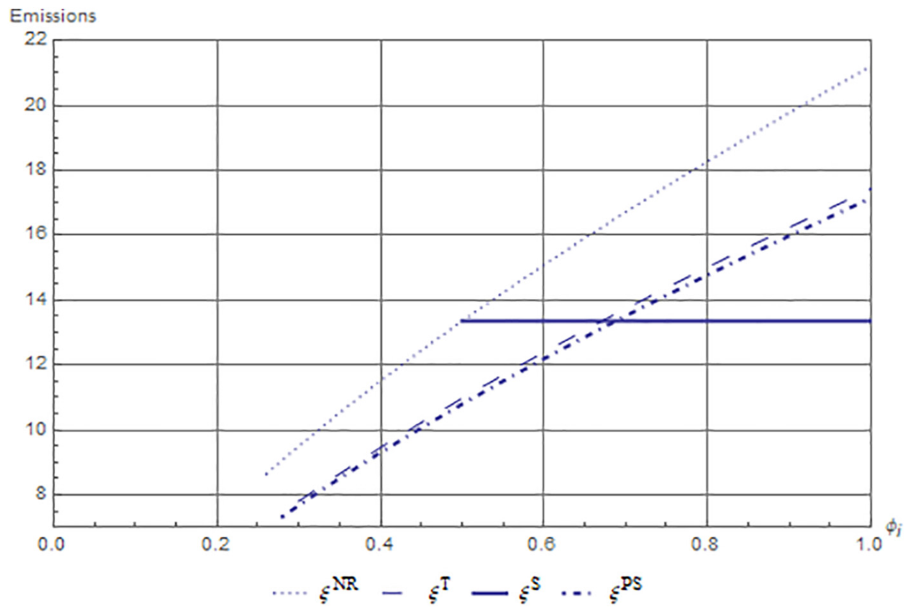

Fig. 1. Distribution of emissions across the different types of firms (NR: Non-regulation, T: optimal tax, S: emission standards, PS: performance standards).

discussed before, this is explained by the fact that under taxes firms have to pay for all the emissions they release and the taxation fully internalizes the environmental damage caused by the generated emissions, while in the case of performance standards emissions below the level imposed by the standard are free of charge.

Finally, in Table 4 we also present some numerical results for the two technology options. In particular, we compute the thresholds $\hat{\theta}^S$, $\hat{\theta}^T$, and $\hat{\theta}^{PS}$. Since the adoption of these technologies implies an investment cost for the firms, only those firms whose surplus exceeds the investment cost will be able to invest. However, as expected, our simulations indicate that $\hat{\theta}^S > \hat{\theta}^T > \hat{\theta}^{PS}$ implying that firms are most likely to invest in the emissions-saving technology under emission standards.

6. Conclusions

In this paper we study the effects of the choice of policy instruments on the size distribution of firms, as well as on the incentives to invest in either energy-saving or neutral technologies. Imposing the same regulatory goal regarding the reduction of aggregate emissions, we have shown that each regulation affects firms of heterogeneous size differently, favoring either small or large firms. For instance, compared with taxes or performance standards, uniform emission standards are much more stringent for larger firms which despite using the input that generates emissions less intensively emit more than small firms in absolute terms. In contrast, performance standards and to a greater extent emission taxes are much more

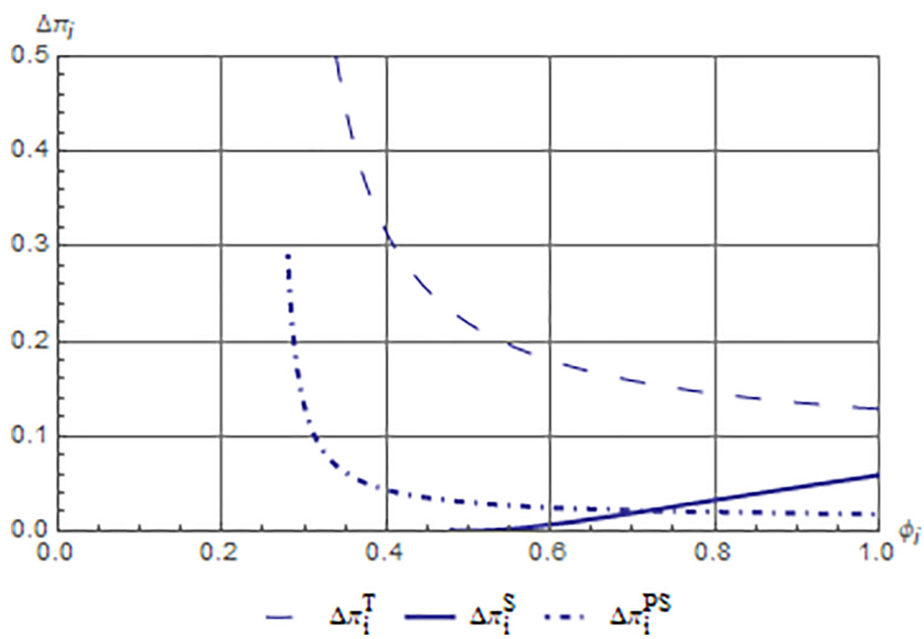

Fig. 2. Percentage reduction in firm i's profits under environmental policy vis-a-vis no regulations.

stringent for smaller firms than for larger firms. Moreover, we have shown that a different number of firms go out of business under different policy instruments.

To sum up, the internalization of the social cost coming from the polluting activity of firms leads to lower production levels for each "type" of firm. Emission taxes affect small firms with significantly low profits (needed to cover the fixed costs) the most, as the use of energy now becomes more expensive. Emission standards affect the most those large firms for which the standard is binding. These firms would have to distort their choice of inputs significantly as well as reduce their production and profits in order to comply with the standard. Finally, performance standards favor large firms that produce high levels of output and do not find the regulation so restrictive. Thus, compared with the other two policy instruments, they lead to higher aggregate output. Last but not the least, assuming that firms can invest in two different technologies, a neutral technology and an emission-saving-biased technology, we show that emission standards favor the use of emissions-saving technologies the most.

The fact that each regulation policy affects the size distribution differently has important welfare consequences. In our setting, the underlying size distribution of firms in the industry is the result of the existence of heterogeneity in available physical capital with respect to energy intensity. Any environmental policy introducing regulatory asymmetries favoring small firms might have significant detrimental effects on total welfare, yet it helps preserve small businesses, which could be desirable because of antitrust of other non-economic reasons. Those firms are shown to become inefficient and exit the market in the presence of emission taxes and (to a lower extent in the presence of) performance standards. Alternatively, one could exempt smaller firms from the regulation, though this creates additional distortions and discontinuities on the size distribution - an interesting issue for future research.

Appendix A

A.1. Proposition 1

Note that $\Delta\pi_i^T = \frac{\pi_i^{NR}-\pi_i^T}{\pi_i^{NR}} = 1 - \frac{\pi_i^T}{\pi_i^{NR}}$. Differentiating $\Delta\pi_i^T$ with respect to ϕ_i leads to:

$$\frac{\partial \Delta\pi_i^T}{\partial \phi_i} = \frac{\pi_i^T \frac{\partial \pi_i^{NR}}{\partial \phi_i} - \pi_i^{NR} \frac{\partial \pi_i^T}{\partial \phi_i}}{\left[\pi_i^{NR}\right]^2}. \tag{A1}$$

Differentiating Eqs. (9) and (14) with respect to ϕ_i and replacing in (A1) leads to:

$$\frac{\partial \Delta\pi_i^T}{\partial \phi_i} = \left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\frac{\pi_i^T\left[\pi_i^{NR}+F\right] - \pi_i^{NR}\left[\pi_i^T+F\right]}{\phi_i\left[\pi_i^{NR}\right]^2}\right], \tag{A2}$$

which simplifies to:

$$\frac{\partial \Delta\pi_i^T}{\partial \phi_i} = -\left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{F}{\phi_i}\frac{\Delta\pi_i^T}{\pi_i^{NR}} < 0. \tag{A3}$$

A.2. Proposition 2

Note that $\Delta\pi_i^S = \frac{\pi_i^{NR}-\pi_i^S}{\pi_i^{NR}} = 1 - \frac{\pi_i^S}{\pi_i^{NR}}$. Differentiating $\Delta\pi_i^S$ with respect to ϕ_i leads to:

$$\frac{\partial \Delta\pi_i^S}{\partial \phi_i} = \frac{\left[\pi_i^S \frac{\partial \pi_i^{NR}}{\partial \phi_i} - \pi_i^{NR} \frac{\partial \pi_i^S}{\partial \phi_i}\right]}{\left[\pi_i^{NR}\right]^2}. \tag{A4}$$

Differentiating Eqs. (9) and (25) with respect to ϕ_i and replacing in Eq. (A4) leads to:

$$\frac{\partial \Delta\pi_i^S}{\partial \phi_i} = \left[\frac{\left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{\pi_i^S\left[\pi_i^{NR}+F\right]}{\phi_i} - \left[\frac{\alpha}{1-\beta}\right]\frac{\pi_i^{NR}\left[\pi_i^S+z\left[\bar{\xi}\gamma^{-1}\right]+F\right]}{\phi_i}}{\left[\pi_i^{NR}\right]^2}\right], \tag{A5}$$

which simplifies to:

$$\frac{\partial \Delta\pi_i^S}{\partial \phi_i} = \left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\frac{\alpha\left[p\theta\beta^\beta\phi_i^\alpha\left[\bar{\xi}\gamma^{-1}\right]^\alpha w^{-\beta}\right]^{\frac{1}{1-\beta}} - z\left[\bar{\xi}\gamma^{-1}\right]}{\phi_i\pi_i^{NR}}\right] - \left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{F}{\phi_i}\frac{\Delta\pi_i^S}{\pi_i^{NR}}. \tag{A6}$$

The first term in brackets on the RHS of Eq. (A6) corresponds to the regulatory asymmetry effect (*RA*), which captures the fact that emission standards distort the emission intensity of larger firms the most.

Adding and substracting $\left[\frac{\mathbf{1}}{1-\alpha-\beta}\right]\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right] + F\right]$ to Eq. (A6) yields:

$$\frac{\partial \Delta\pi_i^S}{\partial \phi_i} = \frac{\alpha}{\phi_i\left[\pi_i^{NR}\right]^2}\left[\begin{array}{c}\left[\frac{1}{1-\alpha-\beta}\right]\left[\pi_i^S\left[\pi_i^{NR}+F\right] - \pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]\right] \\ +\left[\frac{1}{1-\alpha-\beta}\right]\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right] - \left[\frac{1}{1-\beta}\right]\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]\end{array}\right].$$

Or:

$$\frac{\partial \Delta\pi_i^S}{\partial \phi_i} = \frac{1}{\phi_i\left[\pi_i^{NR}\right]^2}\left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\left[\frac{\alpha}{1-\beta}\right]\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right] - \left[F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]\right]\right].$$

$\frac{\partial \Delta\pi_i^S}{\partial \phi_i}$ is positive if:

$$\alpha > \frac{F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]}{\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]}\left[1-\beta\right]. \tag{A7}$$

Note that $\frac{F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]}{\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]} < 1$. Hence, the constraint in Eq. (A7) should be consistent with the condition $\alpha < 1-\beta$ since $\frac{F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]}{\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]}$ is something smaller than 1.

For the concavity condition $2\alpha + \beta < 1$ to hold we need:

$$\alpha < \frac{1-\beta}{2}. \tag{A8}$$

Combining conditions (A7) and (A8) yields:

$$\frac{F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]}{\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]}\left[1-\beta\right] < \alpha < \frac{1-\beta}{2}.$$

Then the two conditions will hold simultaneously if and only if:

$$\frac{F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]}{\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]} < \frac{1}{2}. \tag{A9}$$

Eq. (A9) can be represented as:

$$2F\left[\pi_i^{NR}-\pi_i^S\right] + 2\pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right] < \pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right].$$

Or:

$$0 < \pi_i^{NR}\left[\pi_i^S - z\left[\bar{\xi}\gamma^{-1}\right] - F\right] + 2F\pi_i^S,$$

which always holds since $\pi_i^S \geq z\left[\bar{\xi}\gamma^{-1}\right] + F$.

Hence, $\frac{F\left[\pi_i^{NR}-\pi_i^S\right] + \pi_i^{NR}z\left[\bar{\xi}\gamma^{-1}\right]}{\pi_i^{NR}\left[\pi_i^S + z\left[\bar{\xi}\gamma^{-1}\right]+F\right]} < \frac{1}{2}$ and $\frac{\partial \Delta\pi_i^S}{\partial \phi_i} > 0$. This is to say, the RA is larger than the SE effect implying that emission standards reduce the profits of larger firms by a larger percentage than those for smaller firms.

A.3. Proposition 3

Differentiating $\Delta\pi_i^{PS}$ with respect to ϕ_i leads to:

$$\frac{\partial \Delta\pi_i^{PS}}{\partial \phi_i} = \frac{\pi_i^{PS}\frac{\partial \pi_i^{NR}}{\partial \phi_i} - \pi_i^{NR}\frac{\partial \pi_i^{PS}}{\partial \phi_i}}{\left[\pi_i^{NR}\right]^2}. \tag{A11}$$

Differentiating Eqs. (9) and (34) with respect to ϕ_i and replacing in Eq. (A11) leads to:

$$\frac{\partial \Delta\pi_i^{PS}}{\partial \phi_i} = \left[\frac{\alpha}{1-\alpha-\beta}\right]\left[\frac{\pi_i^{PS}\left[\pi_i^{NR}+F\right] - \pi_i^{NR}\left[\pi_i^{PS}+F\right]}{\phi_i\left[\pi_i^{NR}\right]^2}\right], \tag{A12}$$

which simplifies to:

$$\frac{\partial \Delta\pi_i^{PS}}{\partial \phi_i} = -\left[\frac{\alpha}{1-\alpha-\beta}\right]\frac{F}{\phi_i}\frac{\Delta\pi_i^{PS}}{\pi_i^{NR}} < 0. \tag{A13}$$

Appendix B

B.1. Proposition 4 & 5

It is easy to show that when the average emission intensity under PS, κ, is set to be equal to the average emission intensity under taxes, $\frac{p\alpha\gamma}{z+\tau\gamma}$, then $\phi_0^T > \phi_0^{PS}$ and $\xi_i^T < \xi_i^{PS}$, which means that individual emissions under PS are always higher than the corresponding ones under T and at the same time there are more firms active in the market in the presence of PS: Thus, we should have $\kappa < \frac{p\alpha\gamma}{z+\tau\gamma}$ in order to satisfy the regulatory goal which is the ex post reduction of emission to the same level $\bar{E} = \Sigma^*$. In this case the performance standard can be given by $\kappa = \psi\frac{p\alpha\gamma}{z+\tau\gamma}$, where $0 < \psi < 1$. Then κ will be defined by equating $\Sigma^T = \Sigma^{PS}$
or

$$\gamma\left[p\theta\beta^\beta w^{-\beta}\alpha^{1-\beta}[z+\tau\gamma]^{-[1-\beta]}\right]^{\frac{1}{1-\alpha-\beta}}\int_{\phi_0^T}^{\bar{\phi}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}}d\phi = \gamma\left[\frac{\kappa\gamma^{-1}\theta\beta^\beta\left[p\kappa^{-1}\gamma - z\right]^\beta}{[1-\alpha]^\beta w^\beta}\right]^{\frac{1}{1-\alpha-\beta}}\int_{\phi_0^{PS}}^{\bar{\phi}}\phi_i^{\frac{\alpha}{1-\alpha-\beta}}d\phi$$

$$\frac{1}{h}\left[p\alpha^{1-\beta}[z+\tau\gamma]^{-[1-\beta]}\right]^{\frac{1}{1-\alpha-\beta}}\left[\bar{\phi}^h - \left[\phi_0^T\right]^h\right] = \frac{1}{h}\left[\frac{\kappa\gamma^{-1}\left[p\kappa^{-1}\gamma - z\right]^\beta}{[1-\alpha]^\beta}\right]^{\frac{1}{1-\alpha-\beta}}\left[\bar{\phi}^h - \left[\phi_0^{PS}\right]^h\right]$$

By raising to the power of $1-\alpha-\beta$ and substituting $z+\tau\gamma = \psi\frac{p\alpha\gamma}{\kappa}$ in the LHS, we get:

$$\left[p\alpha^{1-\beta}\left[\psi\frac{p\alpha\gamma}{\kappa}\right]^{-[1-\beta]}\right]\left[\bar{\phi}^h - \left[\phi_0^T\right]^h\right]^{1-\alpha-\beta} = \left[\frac{\kappa\gamma^{-1}\left[p\kappa^{-1}\gamma - z\right]^\beta}{[1-\alpha]^\beta}\right]\left[\bar{\phi}^h - \left[\phi_0^{PS}\right]^h\right]^{1-\alpha-\beta}$$

$$\left[p^\beta\gamma^\beta[1-\alpha]^\beta\right]\left[\bar{\phi}^h - \left[\phi_0^T\right]^h\right]^{1-\alpha-\beta} = \left[\psi^{[1-\beta]}\kappa^\beta\left[p\kappa^{-1}\gamma - z\right]^\beta\right]\left[\bar{\phi}^h - \left[\phi_0^{PS}\right]^h\right]^{1-\alpha-\beta}$$

We raise all the terms to the power of $\frac{1}{\beta}$:

$$[p\gamma[1-\alpha]]\left[\bar{\phi}^h - \left[\phi_0^T\right]^h\right]^{\frac{1-\alpha-\beta}{\beta}} = \left[\psi^{\frac{[1-\beta]}{\beta}}\kappa\left[p\kappa^{-1}\gamma - z\right]\right]\left[\bar{\phi}^h - \left[\phi_0^{PS}\right]^h\right]^{\frac{1-\alpha-\beta}{\beta}}$$

$$[p\gamma[1-\alpha]]\left[\bar{\phi}^h - \left[\phi_0^T\right]^h\right]^{\frac{1-\alpha-\beta}{\beta}} = \left[\psi^{\frac{[1-\beta]}{\beta}}[p\gamma - \kappa z]\right]\left[\bar{\phi}^h - \left[\phi_0^{PS}\right]^h\right]^{\frac{1-\alpha-\beta}{\beta}}$$

$$\kappa = \frac{p\gamma}{z} - \left[\frac{p\gamma[1-\alpha]}{\psi^{\frac{[1-\beta]}{\beta}}z}\right]\left[\frac{\bar{\phi}^h - \left[\phi_0^T\right]^h}{\bar{\phi}^h - \left[\phi_0^{PS}\right]^h}\right]^{\frac{1-\alpha-\beta}{\beta}} \tag{B1}$$

If we assume that κ takes the value above, we will show in a number of steps that the individual emissions in the case of PS are lower than in the case of taxes, or $\xi_i^T > \xi_i^{PS}$:

$$\gamma\Big[p\theta\beta^\beta w^{-\beta}\alpha^{1-\beta}[z+\tau\gamma]^{-[1-\beta]}\phi_i^\alpha\Big]^{\frac{1}{1-\alpha-\beta}} > \gamma\left[\frac{\kappa\gamma^{-1}\theta\beta^\beta\left[p\kappa^{-1}\gamma-z\right]^\beta}{[1-\alpha]^\beta w^\beta}\phi_i^\alpha\right]^{\frac{1}{1-\alpha-\beta}}$$

$$p\alpha^{1-\beta}[z+\tau\gamma]^{-[1-\beta]} > \frac{\kappa\gamma^{-1}\left[p\kappa^{-1}\gamma-z\right]^\beta}{[1-\alpha]^\beta}$$

Substituting $z+\tau\gamma=\psi\frac{p\alpha\gamma}{\kappa}$ in the LHS:

$$p\alpha^{1-\beta}\left[\psi\frac{p\alpha\gamma}{\kappa}\right]^{-[1-\beta]} > \frac{\kappa\gamma^{-1}\left[p\kappa^{-1}\gamma-z\right]^\beta}{[1-\alpha]^\beta}$$

$$p^\beta\gamma^\beta[1-\alpha]^\beta > \psi^{[1-\beta]}\kappa^\beta\Big[p\kappa^{-1}\gamma-z\Big]^\beta$$

and raising to the power of $\frac{1}{\beta}$:

$$p\gamma[1-\alpha] > \psi^{\frac{[1-\beta]}{\beta}}[p\gamma-\kappa z]$$

$$\kappa > \left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\frac{p\gamma}{z} \tag{B2}$$

Using Eq. (B1), we get:

$$\frac{p\gamma}{z}-\left[\frac{p\gamma[1-\alpha]}{\psi^{\frac{[1-\beta]}{\beta}}z}\right]\left[\frac{\bar{\phi}^h-[\phi_0^T]^h}{\bar{\phi}^h-\left[\phi_0^{PS}\right]^h}\right]^{\frac{1-\alpha-\beta}{\beta}} > \left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\frac{p\gamma}{z}$$

$$1-\left[\frac{[1-\alpha]}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\left[\frac{\bar{\phi}^h-[\phi_0^T]^h}{\bar{\phi}^h-\left[\phi_0^{PS}\right]^h}\right]^{\frac{1-\alpha-\beta}{\beta}} > \left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]$$

$$\left[\frac{\psi^{\frac{[1-\beta]}{\beta}}-\psi^{\frac{[1-\beta]}{\beta}}-\alpha+1}{\psi^{\frac{[1-\beta]}{\beta}}}\right] > \left[\frac{[1-\alpha]}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\left[\frac{\bar{\phi}^h-[\phi_0^T]^h}{\bar{\phi}^h-\left[\phi_0^{PS}\right]^h}\right]^{\frac{1-\alpha-\beta}{\beta}}$$

$$\left[\frac{1-\alpha}{\psi^{\frac{[1-\beta]}{\beta}}}\right] > \left[\frac{[1-\alpha]}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\left[\frac{\bar{\phi}^h-[\phi_0^T]^h}{\bar{\phi}^h-\left[\phi_0^{PS}\right]^h}\right]^{\frac{1-\alpha-\beta}{\beta}}$$

$$1 > \left[\frac{\bar{\phi}^h-[\phi_0^T]^h}{\bar{\phi}^h-\left[\phi_0^{PS}\right]^h}\right]^{\frac{1-\alpha-\beta}{\beta}}$$

$$\left[\phi_0^{PS}\right]^h < \left[\phi_0^T\right]^h$$

$$\left[\phi_0^{PS}\right] < \left[\phi_0^T\right] \tag{B3}$$

We have proved that higher individual emission under T, under the condition that the regulatory goal is satisfied, i.e. the κ value is determined so as to lead to equal aggregate emissions ex post, imply higher cutoff value, in the case of T. Notice that

$$\left[\phi_0^T\right] > \left[\phi_0^{PS}\right]$$

$$\left[\frac{F^{1-\alpha-\beta}(z+\tau\gamma)^\alpha w^\beta}{p\theta\beta^\beta\alpha^\alpha(1-\alpha-\beta)^{1-\alpha-\beta}}\right]^{\frac{1}{\alpha}} > \left[\frac{F^{1-\alpha-\beta}(1-\alpha)^{1-\alpha}w^\beta\gamma}{\kappa\theta\beta^\beta(p\kappa^{-1}\gamma-z)^{1-\alpha}(1-\alpha-\beta)^{1-\alpha-\beta}}\right]^{\frac{1}{\alpha}}$$

$$\left[\frac{[z+\tau\gamma]^\alpha}{p\alpha^\alpha}\right]^{\frac{1}{\alpha}} > \left[\frac{[1-\alpha]^{1-\alpha}\gamma}{\kappa(p\kappa^{-1}\gamma-z)^{1-\alpha}}\right]^{\frac{1}{\alpha}}$$

$$[z+\tau\gamma]^{\alpha}p^{-1}\alpha^{-\alpha} > [1-\alpha]^{1-\alpha}\gamma\kappa^{-1}\left[p\kappa^{-1}\gamma - z\right]^{-[1-\alpha]}$$

substituting $z+\tau\gamma = \psi\frac{p\alpha\gamma}{\kappa}$ in the LHS:

$$\left[\psi\frac{p\alpha\gamma}{\kappa}\right]^{\alpha}p^{-1}\alpha^{-\alpha} > [1-\alpha]^{1-\alpha}\gamma\kappa^{-1}\left[p\kappa^{-1}\gamma - z\right]^{-[1-\alpha]}$$

$$\psi^{\frac{\alpha}{1-\alpha}}[p\gamma-\kappa z] > p\,[1-\alpha]\,\gamma$$

$$\psi^{\frac{\alpha}{1-\alpha}}\kappa z < \left[\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1\right]p\gamma$$

$$\kappa < \left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right]\frac{p\gamma}{z} \tag{B4}$$

From Eqs. (B2) and (B4), we know that $\left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right]\frac{p\gamma}{z} > \kappa > \left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\frac{p\gamma}{z}$. This implies that

$$\left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right]\frac{p\gamma}{z} > \left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\frac{p\gamma}{z}$$

$$\left[1-\frac{1-\alpha}{\psi^{\frac{\alpha}{1-\alpha}}}\right] > \left[1-\frac{1-\alpha}{\psi^{\frac{[1-\beta]}{\beta}}}\right]$$

$$\frac{1-\alpha}{\psi^{\frac{\alpha}{1-\alpha}}} < \frac{1-\alpha}{\psi^{\frac{[1-\beta]}{\beta}}}$$

$$\psi^{\frac{1-\beta}{\beta}} < \psi^{\frac{\alpha}{1-\alpha}}$$

which is always true for the α and β values of our model (where $\frac{1-\beta}{\beta} > \frac{\alpha}{1-\alpha}$) and given that $0<\psi<1$. We show that:

$$\left[\pi_i^T\right] < \left[\pi_i^{PS}\right]$$

$$p\alpha^{\alpha}[z+\tau\gamma]^{-\alpha} < \kappa\gamma^{-1}\left[\frac{p\kappa^{-1}\gamma-z}{1-\alpha}\right]^{1-\alpha}$$

$$p\alpha^{\alpha}\left[\psi\frac{p\alpha\gamma}{\kappa}\right]^{-\alpha} < \kappa\gamma^{-1}\left[\frac{p\kappa^{-1}\gamma-z}{1-\alpha}\right]^{1-\alpha}$$

$$\kappa < \left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right]\frac{p\gamma}{z}$$

which holds from Eq. (B4), meaning that $\left[\pi_i^T\right] < \left[\pi_i^{PS}\right]$. This is not a surprising result since in the case of taxes the polluters have to pay a tax for every single unit of emissions they generate.

To sum up, we have so far presented the conditions under which $\xi_i^{PS} < \xi_i^T$, $[\phi_0^T] > \left[\phi_0^{PS}\right]$ and $[\pi_i^T] < \left[\pi_i^{PS}\right]$ in the case where the κ value satisfies the regulatory goal. Below we show that this is the only equilibrium and that the same regulatory goal cannot be achieved with higher emissions per firm under PS and combined with a lower number of active firms instead.

More precisely, if $\xi_i^{PS} \geqslant \xi_i^T$, then it is easy to show that Eq. (B2) will be $\kappa \leqslant \left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\frac{p\gamma}{z}$. Using the condition for equal aggregate emission (B1), we show that $\left[\phi_0^{PS}\right] \geqslant [\phi_0^T]$, which implies that $\kappa \geqslant \left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right]\frac{p\gamma}{z}$. In this case, κ takes the following values, $\left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right]\frac{p\gamma}{z} \geqslant \kappa \geqslant \left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right]\frac{p\gamma}{z}$, which means that $\left[\frac{\psi^{\frac{[1-\beta]}{\beta}}+\alpha-1}{\psi^{\frac{[1-\beta]}{\beta}}}\right] \geqslant \left[\frac{\psi^{\frac{\alpha}{1-\alpha}}+\alpha-1}{\psi^{\frac{\alpha}{1-\alpha}}}\right] \Rightarrow \psi^{\frac{1-\beta}{\beta}} \geqslant \psi^{\frac{\alpha}{1-\alpha}}$ which cannot hold for $0<\psi<1$.

Appendix C

C.1. Proposition 6

It is easy to show that $\theta_S^* > \theta_T^*$, for $\tilde{\gamma} < 1$. So, it suffices to show that $\theta_T^* > \theta_{PS}^*$ for the same $\tilde{\gamma}$ values, or:

$$\left[\frac{z+\tau}{z+\tau\tilde{\gamma}}\right]^{\alpha}\theta > \tilde{\gamma}^{-1}\left[\frac{p\kappa^{-1}\tilde{\gamma}-z}{p\kappa^{-1}-z}\right]^{1-\alpha}\theta$$

As in Appendix B, we set $z+\tau\gamma=\psi\frac{p\alpha\gamma}{\kappa}$:

$$\left[\frac{\frac{\psi p\alpha}{\kappa}}{\frac{\psi p\alpha\tilde{\gamma}}{\kappa}}\right]^{\alpha} > \frac{1}{\tilde{\gamma}}\left[\frac{p\kappa^{-1}\tilde{\gamma}-z}{p\kappa^{-1}-z}\right]^{1-\alpha}$$

$$\left[\frac{1}{\tilde{\gamma}}\right]^{\alpha} > \frac{1}{\tilde{\gamma}}\left[\frac{p\kappa^{-1}\tilde{\gamma}-z}{p\kappa^{-1}-z}\right]^{1-\alpha}$$

$$\tilde{\gamma}^{1-\alpha} > \left[\frac{p\kappa^{-1}\tilde{\gamma}-z}{p\kappa^{-1}-z}\right]^{1-\alpha}$$

$$\tilde{\gamma}\left[p\kappa^{-1}-z\right] > \left[p\kappa^{-1}\tilde{\gamma}-z\right]$$

$$z > \tilde{\gamma}z, \text{ which is true for } \tilde{\gamma} < 1.$$

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