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Making Clean Firms Cleaner: Targeting Environmental Regulation to Maximize Returns†

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Policy mechanisms that set maximum pollution quantities per unit of output appear in numerous settings, from state-level smog tests for vehicles to the Environmental Protection Agency's New Source Performance Standards for stationary sources. These policies induce high-pollution-intensity firms to reduce their pollution intensity or leave the market. However, when these firms hold small market shares, this approach may yield modest reductions in total pollution compared to reducing pollution intensities among larger-market-share firms. In this paper, I demonstrate the firm cost and pollution structures in which a policy inducing improvements in pollution intensity is more cost effective when targeting relatively cleaner firms with larger prepolicy market shares.

Pollution often comes from converting polluting inputs to outputs. Firms that convert inputs to outputs more efficiently incur smaller marginal costs and pollute less per unit of output: a more efficient firm is also a less polluting one. In a competitive market, the more efficient and cleaner (lower-pollution-intensity) firms will have weakly larger market shares. Depending on the levels of pollution intensities and market shares, the total quantity of pollution from relatively cleaner firms may exceed that from relatively dirtier firms, as the cleaner firms are more heavily utilized.

This paper seeks to inform a regulator that is deciding where to induce investment in production technologies that lower the pollution intensity of production. Such a policy objective could be achieved through a variety of mechanisms, including investment tax credits, subsidies, and performance rebates. The specific policy mechanism is not discussed explicitly here; rather, the focus is on which types of firms the mechanism should target. While all of these policy mechanisms are second best compared to a price-based instrument, they are the focus of this paper given their omnipresence in pollution control policy.

A key component of this analysis is the relationship between firm competitiveness and pollution intensity. When an industry's production costs are dominated by the marginal costs of converting inputs to outputs, competitiveness simplifies to being determined by a firm's efficiency. For an industry where pollution comes predominantly from inputs, input intensity monotonically increases with pollution intensity. Thus, firm competitiveness monotonically decreases with pollution intensity. It follows then that more competitive, less polluting firms will have higher market shares. The analysis below is relevant for the class of industries in which firm market share is monotonically decreasing with pollution intensity.

An important component of this paper's analysis regards the impact of investment on firm competitiveness. Reducing pollution intensity and improving efficiency can lead to changes in firms' positions on aggregate supply curves. I call such an effect a "reranking," where a reranking toward the left on aggregate supply curves weakly increases market share. Whether reranking occurs depends on the size of the efficiency improvement and the shape of aggregate supply curves. Supply curves that are step functions with large-sized steps are less likely to see reranking compared to smaller-stepped, more continuous-looking curves. Whether reranking leads to changes in market shares depends on whether the reranking impacts firms on the margin. For example, a reranking among two inframarginal firms leaves market shares unchanged.

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In the analysis below, I demonstrate the conditions under which it is more cost effective for a regulator to design a policy mechanism that induces investment among relatively cleaner firms, compared to relatively dirtier firms. The analysis is simplified if one assumes no reranking; such an assumption would be more justified in settings with large-stepped piecewise supply curves and when the policy is expected to yield small changes in efficiencies. That said, the analysis demonstrates the role of reranking in determining the most cost-effective policy design.

I. Theoretical Analysis

Consider a market with two price-taking firms of type one and two. The technologies of the firms lead them to have different efficiencies, $\zeta_1 < \zeta_2$, where lower ζ indicates fewer inputs per output, i.e., more efficient, and ζ is assumed to be greater than 1. If the firms face the same input prices, then firm one's marginal costs are lower, $mc_1 < mc_2$. Firms produce q_i, which is constrained to be less than or equal to their production capacity, $\overline{q_i}$.[1]

Assuming no fixed costs of production, the ranking of units along the aggregate supply curve is according to their ζ values, and market share is weakly decreasing with ζ. Production generates pollution with social costs τ per unit of emissions. Let θ denote the private and social costs of production without considering investment costs:

$$\theta = (q_1\zeta_1 + q_2\zeta_2)(c + e\tau), \tag{1}$$

where q_i is a function of ζ_1 and ζ_2, c denotes the cost of inputs, and e denotes emissions per unit of input.[2] Let us consider a social planner that intends to subsidize investments in pollution reduction. Since pollution is generated by the conversion of inputs to outputs, the objective of the policy is to decrease ζ. The following reviews the conditions under which the planner is better off directing the investment subsidy toward the relatively cleaner firm, firm one in this example.

Investment improves efficiencies, ζ, and as we can see from equation (1), $\partial\theta/\partial\zeta_i \geq 0$.[3] First, assume that the cost of a marginal efficiency improvement is the same across firms, an assumption that will subsequently be relaxed. Also assume that the derivative of ζ_i with respect to investment is nonzero for all i. A social planner should direct investment to firm one when the reduction in costs from investing in firm one is greater than the reduction in costs from investing in firm two: $\partial\theta/\partial\zeta_1 > \partial\theta/\partial\zeta_2$. To evaluate this inequality, I take the derivative of total costs with respect to firm efficiencies, where I rewrite the expression for total costs in equation (1) as a function of the two firms' efficiencies:

$$\frac{\partial q_1(\zeta_1,\zeta_2)}{\partial\zeta_1}\zeta_1 + q_1(\zeta_1,\zeta_2) + \frac{\partial q_2(\zeta_1,\zeta_2)}{\partial\zeta_1}\zeta_2 > \frac{\partial q_2(\zeta_1,\zeta_2)}{\partial\zeta_2}\zeta_2 + q_2(\zeta_1,\zeta_2) + \frac{\partial q_1(\zeta_1,\zeta_2)}{\partial\zeta_2}\zeta_1, \tag{2}$$

where $(c + e\tau)$ drops out, as it is assumed to never be negative. In a marginal analysis, small changes in efficiencies would not lead to firm rerankings, so $\partial q_1/\partial\zeta_1 = \partial q_2/\partial\zeta_2 = \partial q_2/\partial\zeta_1 = \partial q_1/\partial\zeta_2 = 0$. Thus, the decision to invest simplifies to a question of relative production quantities. When a dollar of investment has the same impact on each firm's efficiency, investment should be directed to the firm producing more, which is the relatively cleaner firm when efficiency is monotonically decreasing with pollution intensity. Investment can only lead to reranking if investment in firm two provides greater efficiency improvements than investment in firm one. This could occur if marginal returns to investment are decreasing with efficiency, a case that is considered next.

In this example, we assume that efficiency improvements per investment dollars j are greater when preinvestment efficiency is lower

[1] This setup will imply that when demand exceeds the capacity of the lower-cost firm, the lower-cost firm will produce $\overline{q_i}$.

[2] This setup sets c and e equal across firms. Allowing for variation in e across firms could allow for an extension of this framework to other markets and industries where emissions intensities of inputs vary across firms (for example, in industries with firms using different fuels with unique emissions intensities).

[3] The expression is a strict inequality if q_i is nonzero for any i.

(higher ζ). Let the parameter $\alpha > 1$ govern how quickly efficiency improvements increase when preinvestment efficiency is lower. Suppose that j increases efficiency by reducing ζ_i by an amount $\omega\zeta_i^{\alpha}$, with $\omega \in (0,1)$. Let j_1 denote an investment subsidy to firm one. A social planner should direct investment to firm one if $|\partial\theta/\partial j_1| > |\partial\theta/\partial j_2|$. I evaluate this inequality when setting $\partial\zeta_i/\partial j_i = \omega\zeta_i^{\alpha}$. Taking the derivative of total costs with respect to investment dollars j,

$$(3)\quad \frac{\partial\theta}{\partial j_1} = \left[\frac{\partial q_1}{\partial\zeta_1}\frac{\partial\zeta_1}{\partial j_1}\zeta_1 + q_1\frac{\partial\zeta_1}{\partial j_1} + \frac{\partial q_2}{\partial\zeta_1}\frac{\partial\zeta_1}{\partial j_1}\zeta_2 + q_2\frac{\partial\zeta_2}{\partial j_1}\right](c+e\tau) = \left(q_1\omega\zeta_1^{\alpha}\right)(c+e\tau).$$

The second line uses the fact that since firm one is more efficient before investment, additional investments cannot take additional market share away from firm two, so $\partial q_1/\partial\zeta_1 = \partial q_2/\partial\zeta_1 = 0$. And, $\partial\zeta_2/\partial j_1 = 0$ by construction. If investment in firm two does not lead to firm reranking, then $\partial\theta/\partial j_2$ has a similar expression, and we have that investment should be directed to firm one if the following holds:

$$(4)\quad \left|\frac{\partial\theta}{\partial j_1}\right| > \left|\frac{\partial\theta}{\partial j_2}\right| \quad\rightarrow\quad \frac{q_1}{q_2} > \left(\frac{\zeta_2}{\zeta_1}\right)^{\alpha}.$$

Thus, investment should be directed to firm one if firm one's size is sufficiently large relative to the difference between efficiencies. A larger α increases the magnitude of the difference in preinvestment efficiencies on the right-hand side: when returns to investment diminish more quickly in preinvestment efficiency, the relative size difference must be even larger to make investment in firm one still optimal.

When investment in firm two leads to market share reranking, then the following must be true for investment in firm one to remain optimal:

$$(5)\quad \left|q_1\omega\zeta_1^{\alpha}\right| > \left|q_2\omega\zeta_2^{\alpha} + \zeta_1\frac{\partial q_1}{\partial j_2} + \zeta_2\frac{\partial q_2}{\partial j_2}\right|.$$

With reranking and market share shifts, the second and third terms on the right-hand side will be negative and positive, respectively, where $\partial q_1/\partial j_2$ and $\partial q_2/\partial j_2$ represent market share changes from investment in other and own firm. The decision rule again depends on relative sizes, efficiencies, and the quantity of market share shifted from one firm to another. Again, in this expression, since $\zeta_2 > \zeta_1$, a larger α decreases the likelihood that the left-hand side is larger, i.e., that it is optimal to invest in the cleaner firm, firm one.

II. Application to California Wholesale Electricity Market

The results of the theoretical analysis imply a decision rule to determine where investments should be directed. I review the trade-off implied by the rule in the California wholesale electricity market. I use data from the US Environmental Protection Agency's Continuous Emissions Monitoring Systems (CEMS), which provide hourly production quantities and fuel inputs at the electric generating unit level, used to estimate average unit efficiencies (US Environmental Protection Agency 2020). I first test whether a key condition for the above analysis holds in this market, that is, whether competitiveness is increasing with efficiency. I estimate the correlation between average monthly market share and log average heat rates in 2012, which yields a precisely estimated negative coefficient of -0.0191 (95 percent confidence interval: $[-0.0196, -0.0185]$), providing evidence that market share is increasing with efficiency.[4]

Next, I identify investments over this period. I identify firms that improved their annual average efficiency in 2016 compared to 2012: 73 of the 200 units in the dataset reduced their annual average heat rate in 2016 compared to 2012 by more than 200 British thermal units per kilowatt-hours.[5] I identify these units as investors. During this period, electric generating units were regulated by California's cap-and-trade program, so social costs τ are included in the firm problem. However, the California carbon price during this period averaged around \$13 per ton (California Carbon Dashboard 2021), much lower than estimates of the social cost of carbon (US Environmental Protection Agency 2017), providing a smaller price signal than that

[4] More precisely, market share here is share of residual demand, demand less renewable production, which is not included in these data.

[5] Heat rate observations above (below) the ninety-ninth (first) percentiles are removed.

which would be required to fully internalize the externality.

I use *k*-means clustering to bin firms into 20 types based on their heat rates, and then I estimate investment probabilities by type. The scatter plot in Figure 1 in the Appendix indicates a bell-shaped relationship between efficiency and investment, where investment probabilities initially increase in inefficiency and then decrease with little investment among the least efficient types. The shape is consistent with the trade-off discussed in the theory: investing in less efficient units is potentially less costly, though the returns may accrue more slowly due to lower market shares. These data suggest that investment may be most cost effective among middle-range efficiency levels, where returns to investment are larger than they are among the most efficient units but market shares are larger than they are among the least efficient units.

A key component for decision-making regards estimating investment costs and how quickly costs increase in preinvestment efficiency. In some settings, regulators may observe abatement technology costs, in which case all the components of the decision rule are observed. In other settings when these data are not available, this paper's framework provides intuition for decision-making. When the costs of investment are expected to yield similar returns across firm types, investment should be directed toward larger-market-share firms. If investment costs increase rapidly in efficiency, investment may be better directed toward less efficient firms, but only when those firms are expected to satisfy a sufficient share of market demand.

III. Conclusion

Many policy mechanisms that address production externalities implicitly target the dirtiest firms. This paper provides a simple decision rule for designing policy. When more polluting firms have less market share and the returns to investment do not diminish quickly with preinvestment efficiency, it will be more cost effective to invest in relatively more efficient firms. The California wholesale electricity sector exhibits investment behavior consistent with the trade-off demonstrated in this paper between investing in high-market-share firms while taking advantage of potentially lower cost-efficiency improvements available among lower-market-share, less efficient firms.

Appendix

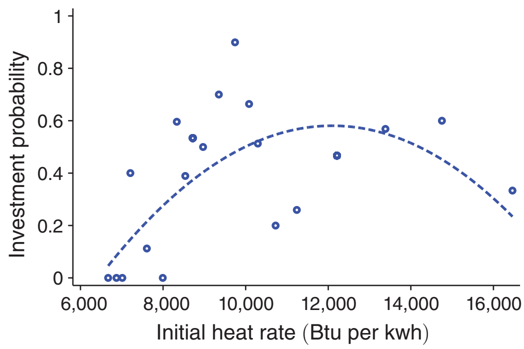

Figure A1. Investment Probability by Heat Rate, 2013–2016

Note: This figure plots investment probability by firm type; 20 firm types are identified using *k*-means clustering by heat rate.

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