Firm Preferences for Environmental Policy: Industry Uniform or Firm Specific?*

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August 31, 2016

Abstract

This paper examines the effect of uniform and firm-specific environmental regulation on the production decisions, and profits, of polluting and green firms. While both types of regulation increase firms' costs and thus entail a negative effect on profits, firm-specific regulation can also yield a positive effect for relatively inefficient firms by alleviating their cost disadvantage. When such cost disadvantage is sufficiently large, we show that the positive effect of firm-specific regulation dominates its negative effect, leading inefficient (efficient) firms to support (oppose) socially optimal regulation. Furthermore, our findings indicate that such support for environmental policy can originate not only from the most common ally (the green firm) but also from polluting firms.

Keywords: Cost asymmetry, cost disadvantage, emission fees, green firms.
JEL classification: L13, D62, H23, Q50.

*We thank the editor, two anonymous referees, and Ana Espinola-Arredondo for their insightful comments and suggestions.

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1 Introduction

As environmental protection agencies gather more accurate information about the damaging effects of different types of pollutants, policies curbing pollution have become more precise in the pollutants they target. As a result, governments less frequently use a uniform regulation to all firms competing in an industry, but instead implement a firm-specific policy in order to induce larger pollution reductions from those firms with more damaging emissions. While the introduction of firm-specific policies is a desirable objective, as it eliminates the inefficiencies typically resulting from uniform policies, it could face the strong opposition of polluting ("brown") firms if they become subject to more stringent fees. Our results, however, show that such opposition does not necessarily exist. Instead, brown firms may actually favor the change from uniform (type-independent) to firm-specific (type-dependent) policies, despite the more stringent emission fees such policy change entails. More generally, we demonstrate that firms' preferences towards environmental policy depend not only on a firm's type, but also on its relative cost efficiency, i.e., whether it suffers a significant cost disadvantage before the policy change.

In order to study firms' preferences towards such policy change, we examine a Cournot duopoly model, in which firms can have different marginal production costs and distinct environmental impacts. For generality, we separately investigate two contexts in which: (1) the production of the green firm is significantly clean (allowing for the green firm to generate zero pollution as a special case); and (2) the production of the green firm, despite being cleaner than that of the brown company, still entails a non-negligible environmental impact, ultimately requiring the regulation of this firm's pollution as well. In each context, we compare firms' profits corresponding to uniform and firm-specific policies in order to elicit whether firms would oppose or favor a policy change towards the latter form of regulation.

Our paper provides three distinct results. First, when the green firm's environmental impact per unit of output produced is not significantly clean, both the brown and green firms are subject to emission fees. In this context, we show that the introduction of firm-specific regulation can have an *activating effect* on firm's production (i.e., helping firms not participating in the industry in the absence of regulation to start producing), while uniform regulation can instead produce a *shutting-down effect* (i.e., forcing firms to stop producing). Importantly, our results suggest that both the brown and green firms are prone to these two effects: when either firm is inefficient relative to its rival, we show that such firm is better off with a firm-specific policy, which helps the firm reduce its significant cost disadvantage. In contrast, the relatively efficient firm prefers a uniform policy as such regulation increases both firms' marginal costs while keeping their cost differential unaffected.

Intuitively, an emission fee (whether it be a firm-specific or uniform) generates a *negative effect* on firms' profits, as it increases marginal cost of production. However, firm-specific fees can also produce a *positive effect* on the brown firm's profits when its green rival is relatively efficient. In particular, while the green firm's production entails a lower per-unit damage than that of the brown firm's, its cost advantage could allow it to produce a larger output, and thus potentially larger aggregate pollution, compared to the brown firm. In this context, our findings suggest that the regulator would impose a stricter emission fee on the green than on the brown firm, producing a larger increase in the marginal costs of the former than the latter. As a consequence, firm-specific regulation helps the brown firm reduce its cost disadvantage, yielding a positive effect on its profits. Comparing the relative size of the positive and negative effects of the regulation, we show that the brown firm benefits from, and thus lobbies for, firm-specific regulation when it suffers a substantial cost disadvantage relative to its green competitor. In contrast, the green firm in this setting would strictly oppose a firm-specific policy as such policy imposes a large negative effect on profits: not only does it inflate the green firm's production costs but it also erodes the firm's cost advantage relative to the brown firm. Hence, given the choice between firm-specific and uniform regulation, the green firm would actually support the latter, which increases both firms' marginal costs, thus keeping the cost differential unaltered.

Our equilibrium predictions provide a possible explanation for the opposition of freight train companies, a group of relatively clean firms, to stringent environmental regulations as well as the support of polluting trucking companies (such as FedEx, Con-way, and Wabash National Corporation) for stricter new fuel regulation (Roth, 2008; Baker and Davenport, 2014).[1] Since railroads are often considered as less polluting and more efficient than freight trucks, one would anticipate the opposite reaction from each type of firm: trains supporting new regulation while trucks opposing it. In fact, freight trains produce, on average, 4-9 times less pollution, and they are also three or more times more fuel efficient than freight trucks (OECD, 1997; Scott and Sinnamon, 2006; and Table A.2 in Appendix A). In light of our findings, the efficiency of trains (relative to trucks) leads them to actually oppose environmental regulation, since regulation would shrink the cost advantage they have against more polluting competitors.[2]

Our theoretical predictions offer analogous results when the green firm is the most inefficient producer in the industry, whereby the green firm supports firm-specific regulation in order to alleviate its cost disadvantage, whilst the brown firm lobbies for uniform policy to preserve its competitive edge. These findings help explain the recent lobbying efforts of U.S. nuclear power companies, such as Exelon Corp., in favor of the new federal carbon limits on electricity generation, as well as the opposition of carbon-intensive power companies, such as American Electric Power and Southern Company (and coal-dependent states, such as Kentucky, North Carolina, Nebraska and Colorado) to new federal carbon emission standards (Johnson, 2013; Shear, 2013).[3] While

[1] In the freight industry, heavy-duty trucks and freight trains are subject to different air pollution regulation from the EPA. In particular, the U.S. Department of Transportation (2005) noted that EPA issued nitrogen oxides (NO_x) and particulate matter emission standards on heavy-duty trucks, making them more stringent in 2007. However, the major non-road freight modes of transportation (trains and marine vessels) were virtually unregulated until the late 1990s, and today remain much less regulated than freight trucks; for a comparison of these emission standards, see Table A.1 in Appendix A.

[2] One can also rationalize the observed firm behavior based on arguments on firm's corporate social responsibility or their expectation of future regulatory changes. Importantly, our findings suggest that, even if such considerations are absent, firms would still have incentives to support environmental policies.

[3] The new EPA air quality regulations, which intend to curb climate-altering emissions from both existing and new fossil-fuel-burning power plants, will set national standards for carbon pollution and allow state governments to create and carry out their own plans to meet the federal requirements (Davenport, 2014). While some states might already satisfy these requirements, others will likely need to make a substantial effort to reduce emissions in the next

coal-fired and nuclear power companies produce electricity, their inputs are subject to distinct EPA regulations as they generate different types of pollution (e.g., carbon emissions for the former and treatment of nuclear waste for the latter).[4] According to the estimates of the U.S. Congressional Research Service (2008), in the absence of carbon controls, pulverized coal-fired power plants have a significant cost advantage relative to nuclear plants, with the estimated annualized costs of $63.10 and $83.22 per megawatt-hour (Mwh), respectively. In contrast, with the introduction of carbon controls, the estimated annualized cost of coal powered electricity generation jumps to a range of $100-120 per Mwh, while that of nuclear power stays constant at $83.22 per Mwh (see Table A.3 in Appendix A). In line with our theoretical predictions, nuclear plants, being the green and most inefficient producers in the industry, support the introduction of stricter carbon regulation in order to ameliorate their significant cost disadvantage relative to coal-fired plants; while the latter fiercely opposes any such regulation.[5]

Second, as the green firm's production becomes significantly clean, the regulator imposes no firm-specific fee on the green firm; while the brown firm is still subject to regulation. As a result, the brown firm can no longer experience the 'activating effect' of a firm-specific regulation; instead, it is harmed under both types of regulatory settings. Yet, the brown firm prefers uniform regulation, which leaves its cost differential unaffected, over firm-specific policy, which shrinks its cost advantage given that the green firm is exempt from emission fees. The green firm, on the other hand, supports firm-specific regulation, which does not affect its costs but harms its brown rival's, a finding that holds regardless of firms' relative efficiency. More generally, our findings emphasize that lobbying efforts critically depend on the green firm's cleanliness: when this firm's production process is significantly clean, it would favor firm-specific policies regardless of its cost differential; whereas when its production is not significantly clean, the green firm would only favor such policies if it suffers a substantial cost disadvantage relative to the brown firm.

Third, our welfare analysis demonstrates that, while a uniform policy is welfare improving relative to no regulation at all, it entails inefficiencies as firms with different production costs and environmental damages are subject to the same (uniform) emission fee. In contrast, introducing a firm-specific policy prevents such suboptimal results, as it sets a different fee on each type of firm if their costs and/or environmental damages differ. Given the desirable welfare properties of firm-specific regulation, the regulator may use our theoretical predictions to forecast which type of firms will likely favor the implementation of such policies. In particular, our findings highlight the unintended consequences of non-environmental policies in building political resistance towards

few years.

[4]According to the U.S. Environmental Protection Agency (2008), nuclear plant operations are subject to a myriad of environmental regulations. Specifically, under the Clean Water Act, EPA regulates thermal discharges; cooling water intake location, design, construction, and capacity; storm water discharges; dredging, filling, and wetlands impacts. Under the Safe Drinking Water Act, EPA protects the quality of the nation's drinking water supplies from nuclear plants' activities. Under the Clean Air Act, EPA has the authority to list hazardous air pollutants and develop and enforce emission limits for each of them. In addition, EPA has an authority to issue generally applicable environmental radiation standards.

[5]See Perino and Talavera (2014) for an empirical analysis of plant specific regulation, and an assessment of its welfare benefits, for U.S. coal-fired power plants.

environmental regulation. For instance, in industries where the green firm's production is not significantly clean, policies that make a firm more efficient (a common goal in many government agencies) would inadvertently build political opposition to firm-specific regulation. By contrast, non-environmental policies that increase firms' costs (e.g., administrative fees) could unintentionally help to build support towards firm-specific environmental policies.

From a policy perspective, our paper helps to identify in which contexts the welfare benefits from implementing firm-specific regulations likely exceed their costs, e.g., the need to dedicate government staff and technicians to data collection, processing, and other new administrative procedures. Our findings suggest that, when firms are cost asymmetric, firm-specific policies can lead to large welfare gains, but only if the green firm is moderately clean. In contrast, when the green firm is extremely clean, the benefits of implementing a firm-specific regulation become smaller, suggesting that the regulators may prefer to apply a uniform regulation to all industry participants. Hence, when firms are cost asymmetric, one should expect uniform regulations in industries where the green firm is significantly clean, but firm-specific regulations in industries where the green firm generates moderate environmental damage.[6]

Related literature. This paper lies at the intersection of a literature analyzing firm-specific policies, and that examining firm interests in using environmental regulation as a tool to raise their rival's costs. Studies on fine-tuned environmental policies (e.g., Tietenberg, 1974; Hochman et al., 1977; Henderson, 1977; Hochman and Ofek, 1979) have emphasized that an efficient environmental policy should penalize each emission source according to its specific marginal contribution to social damages.[7] Marrouch and Sinclair-Desgagné (2012), analyzing the role of geographical information in policy design, show that if polluters are price-takers, the optimal emission tax will disregard a source's location; whereas, when polluters have some market power, then the optimal pollution taxation scheme needs to be fine-tuned according to location. In line with this literature, we analyze an asymmetric Cournot duopoly model of environmental pollution, comparing the welfare effects of uniform and fine-tuned (firm-specific) regulation and also identifying firm's preferences towards each regulatory setting.

Ulph (2000), studying environmental policies at the state and federal level, contends that uniform federal policies are rarely justifiable given the different environmental characteristics in each state.[8,9] Similarly, in our paper, we show that firm-specific regulation is welfare improving compared

[6]The opposite argument applies to settings where firms are cost symmetric, where uniform (firm-specific) policies are recommended when the green firm is moderately (significantly, respectively) clean.

[7]Although the technical and administrative costs involved in collecting and processing the needed information have traditionally limited the practicality of fine-tuned policies (Laffont and Tirole, 1993, chapter 1), calculation of source-specific marginal damages of emissions is gradually becoming possible and practical (Muller and Mendelsohn, 2009).

[8]Specifically, Ulph (2000) assumes that the federal government cannot observe each state's environmental characteristics, and compares three types of policies: (1) policy set independently and non-cooperatively by each state government; (2) federal policy that induces cooperative solution (i.e., setting different policies for states with different environmental characteristics); and (3) a uniform federal policy. The paper shows that, although the difference in federal environmental policies across states diminishes with asymmetric information (relative to full information), this does not justify setting a uniform federal policy. In fact, as the paper reports, the welfare loss from harmonization rises exponentially with the difference in states' environmental characteristics.

[9]In line with this study, Huhtala and Samakovlis (2002) provide theoretical and empirical analysis of the economic

to uniform regulation. Importantly, we demonstrate that the switch to firm-specific regulation is not only sought after by regulators, but also by certain types of firms who can experience a reduction in their cost disadvantage as a result of the change in environmental policy (from uniform to firm-specific).

Our paper is also related to the literature analyzing firms' incentives to raise their rivals' costs.[10] In particular, these studies examine firms' incentives to strategically pursue a costly action, such as compliance costs, vertical integration, or technological change, in order to increase their rival's costs in their subsequent competition. We show that both green and brown, while bearing a cost of environmental regulation (measured by the negative effect of emission fees on profits), can support a policy change from uniform to firm-specific emission fees in order to shrink their rivals' cost advantage, and thereby increase their own profits. Simpson (1995), examining a polluting Cournot duopoly, finds that the introduction of stricter taxation can enhance the cost advantage of the efficient firm and ultimately redistribute the production from the less efficient firm to its more efficient rival, thereby incentivizing the former (latter) to oppose (support, respectively) regulation. Unlike our paper, where we allow firms to differ along two dimensions (production costs and environmental impacts), this literature differentiates firms along a single dimension (production costs).

The present study also relates to the literature examining the effect of environmental regulation on firm profits. For instance, Farzin (2003) analyzes the effect of strict environmental regulation on product quality, and Porter (1991) and Porter and van der Linde (1995a,b) study its impact on innovation and R&D incentives.[11] Our paper illustrates that, even if innovation and product quality incentives are absent, firms might still have other incentives (alleviating cost disadvantage) to support the introduction of firm-specific emission fees. Finally, Muñoz-García and Akhundjanov (2016) explore the preferences of the brown and green firms towards the introduction of firm-specific environmental policy. However, their paper considers a setting where initially there is no regulation, and investigates firms' reaction (either support or opposition) to the introduction of environmental policy. Instead, we focus on industries subject to uniform regulation, and examine firms' as well as the social planner's preferences to switch from uniform to firm-specific regulation.

The remainder of the paper proceeds as follows. In the following section we present the game-theoretic model, while in Sections 3 and 4 we present the industry equilibrium and the planning problem under three different regulatory settings. Firms' preferences towards these regulatory settings are analyzed in Section 5, and welfare implications are reviewed in Section 6. Section 7 provides policy implications and some concluding remarks.

costs of harmonizing paper recycling standards in Europe. The authors show that, although harmonized policy may entail trade effects in the short-term, it is not a social cost minimizing policy measure for promoting waste paper use as such policy does not take into account country-specific characteristics.

[10]While this line of research was initiated by Salop and Scheffman (1983,1987), it was then followed by Krattenmaker and Salop (1986) for the study of exclusionary rights in the use of inputs, Hart and Tirole (1990) and Loertscher and Reisinger (2014) for the analysis of vertical integration, Ordover et al. (1990) and Gaudet and Long (1996) for vertical foreclosures, and Sartzetakis (1997) for the study of dominant firms in emission permit markets.

[11]For a review of the literature, see Heyes (2009).

2 Model

Consider a duopoly industry with a brown (B) and a green (G) firm producing a homogeneous good and competing a la Cournot. The firms' marginal production costs are c_B and c_G, where $c_B, c_G \in (0, 1)$. This allows the brown firm to be more (less) efficient than the green firm, i.e., $c_B < c_G$ ($c_B > c_G$, respectively). Firms face an inverse linear demand function $p(Q) = 1 - Q$, where $Q = q_B + q_G$ is the aggregate output. Following Ulph (1996), we consider that each unit of output generates a unit of emission, and hence $e_K = q_K$, where e_K is firm K's total emissions, for $K = \{B, G\}$. The emission is more damaging when it is produced by the brown than the green firm, i.e., $d_B \geq d_G \geq 0$. Also, similar to Goeschl et al. (2007), total environmental damage is captured by $Env = d_B \times (e_B)^2 + d_G \times (e_G)^2$. This environmental damage function assumes: (a) each firm is geographically distant and, as a consequence, pollution from the brown and green firm do not interact with one another; or (b) firms generate chemically different pollutants.[12]

Moreover, we assume that marginal environmental damages satisfy $d_B \geq d_G \geq 1/2$, so that firm-specific fees are positive for all firms; a context we refer to as 'moderately clean green firm.'[13] If, instead, the marginal damages satisfy $d_B \geq 1/2 > d_G$, the green firm receives a subsidy per unit of output while the brown firm is still subject to a fee; a setting we refer to as 'significantly clean green firm.' In the latter case, firm preferences for environmental regulation are unambiguous: the brown firm opposes regulation, while the green firm favors it under all parameter combinations. (For completeness, we include a detailed analysis of this case in Appendix B.) In contrast, when the green firm's production is not extremely clean $d_B \geq d_G \geq 1/2$, both firms' production entails a sizable environmental impact, thus being subject to regulation. In this context, although the brown firm generates a relatively more damaging pollution than the green firm $d_B \geq d_G$, firms' preferences for environmental policy are far from obvious, as we demonstrate in the following sections.

We examine a two-stage complete information game, where: first, the regulator sets either firm-specific (type-dependent) or uniform (type-independent) emission fees to maximize social welfare; and second, given the emission fee(s) set by the regulator, each firm responds by choosing its output level in order to maximize duopoly profits. The regulator might need to set a uniform policy when he cannot treat different types of firms differently, which may arise because: (i) the political system prevents the use of differentiated regulation; or (ii) the regulator cannot precisely determine each firm's type. In contrast, differentiated emission fees are feasible if the institutional setting allows the regulator to set different fees on distinct types of firms (i.e., firms that differ in their per-unit emissions) and the regulator can observe the specific characteristics of every firm.

[12]Other damage functions yield relatively similar results, as shown in Muñoz-García and Akhundjanov (2016), but are less tractable than the function used in this paper.

[13]A more appropriate notation in this setting would be a 'relatively cleaner firm' as the firm is cleaner than its brown rival but still emits some pollution and, thus, is subject to emission fees. For compactness, however, we use 'green' to refer to the cleanest firm in the industry.

3 Industry equilibrium

In the second stage of the game, every firm with type $K = \{B, G\}$ takes the environmental policy as given, and selects the output level q_K that solves

$$\max_{q_K \geq 0} \; (1 - q_K - q_J)\, q_K - (c_K + t_K)\, q_K,$$

where $J \neq K$, and t_K is the emission fee that firm K faces. Note that when $t_K \neq t_J$, the environmental policy is firm-specific, while when $t_K = t_J$ policy is uniform. First-order condition yields best response function $q_K(q_J, t_K) = \frac{1-c_K-t_K}{2} - \frac{1}{2}q_J$, with the corresponding equilibrium output

$$q_K(t_K, t_J) = \frac{1 - 2c_K + c_J - 2t_K + t_J}{3},$$

where firm K's equilibrium output is decreasing in own emission fee, but increasing in the emission fee imposed on a rival firm. We next analyze the social planner's problem in the first stage of the game under three different regulatory settings.

4 The planning problem

4.1 No regulation

In the absence of environmental regulation, $t_K = t_J = 0$, firms ignore the social costs of their production activities. Inserting the above fees into the brown and green firm's equilibrium output functions yields $q_B^{NR} = \frac{1-2c_B+c_G}{3}$ and $q_G^{NR} = \frac{1+c_B-2c_G}{3}$, respectively, where NR denotes 'no regulation.' Hence, firms' equilibrium output are positive, i.e., $q_B^{NR} > 0$ and $q_G^{NR} > 0$, if and only if c_B satisfies $c_B < \frac{1+c_G}{2} \equiv C_B^{NR}$ and $c_B > 2c_G - 1 \equiv C_G^{NR}$, respectively.

4.2 Firm-specific regulation

The regulator maximizes the social welfare function

$$SW = CS + PS + T - Env,$$

where $CS = \frac{1}{2}(Q(t_B, t_G))^2$ is the consumer surplus, $Q(t_B, t_G) = q_B(t_B, t_G) + q_G(t_G, t_B)$ is the aggregate equilibrium output, PS is the producer surplus, $T = t_B q_B(t_B, t_G) + t_G q_G(t_G, t_B)$ is the total tax revenue from emission fees, and $Env = d_B \times (q_B(t_B, t_G))^2 + d_G \times (q_G(t_G, t_B))^2$ is the aggregate environmental damage arising from the industry production. First order conditions with respect to q_B and q_G yield the socially optimal output levels $q_B^{TD} = \frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)}$ and $q_G^{TD} = \frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)}$, where TD denotes 'type-dependent' regulation. It is straightforward to show that $q_B^{TD} > 0$ and $q_G^{TD} > 0$ if and only if $c_B < \frac{2d_G+c_G}{2d_G+1} \equiv C_B^{TD}$ and $c_B > c_G(2d_B + 1) - 2d_B \equiv C_G^{TD}$, respectively.

The firm-specific emission fees (t_B, t_G) that induce firms to produce the socially optimal output (first best) can be found by simultaneously solving

$$q_B(t_B, t_G) = q_B^{TD} \quad (1)$$
$$q_G(t_G, t_B) = q_G^{TD} \quad (2)$$

which yields $t_B = \frac{(2d_B-1)[2d_G(1-c_B)-c_B+c_G]}{2(d_B+d_G+2d_Bd_G)}$ and $t_G = \frac{(2d_G-1)[2d_B(1-c_G)+c_B-c_G]}{2(d_B+d_G+2d_Bd_G)}$. These emission fees are positive when $c_B < C_B^{TD}$ and $c_B > C_G^{TD}$, respectively.[14]

4.3 Uniform regulation

With two firms exhibiting asymmetries in both production costs and in their environmental damages, a uniform policy generates inefficiencies, since firms cannot be induced to exactly produce the optimal output pair as in the previous subsection. As a consequence, the regulator relies on a "second-best" environmental policy, whereby a single fee ensures that aggregate production is socially optimal, but cannot guarantee that individual firms' production is efficient.

Setting $t_B = t_G = t$ in the firms' equilibrium output function, a uniform emission fee t must solve

$$q_B(t) + q_G(t) = Q^{SO},$$

where $Q^{SO} = q_B^{TD} + q_G^{TD}$ is the socially optimal level of aggregate production. In particular, the emission fee that solves the above equation is $t = \frac{2d_Bd_G(2-c_B-c_G)-d_G(1-2c_B+c_G)-d_B(1+c_B-2c_G)}{2(d_B+d_G+2d_Bd_G)}$, which is positive if and only if $c_B < \frac{d_B+d_G-4d_Bd_G}{2d_G(1-d_B)-d_B} + \frac{d_G(1+2d_B)-2d_B}{2d_G(1-d_B)-d_B}c_G \equiv C^{TI}$, where TI denotes 'type-independent' regulation. Inserting this emission fee into the firms' equilibrium output functions yields $q_B^{TI} = \frac{d_G(1-2c_B+c_G)+d_B[1-c_B-2d_G(c_B-c_G)]}{2(d_B+d_G+2d_Bd_G)}$ and $q_G^{TI} = \frac{d_G(1-c_G)+d_B[1+c_B(1+2d_G)-2c_G(1+d_G)]}{2(d_B+d_G+2d_Bd_G)}$, which are positive if and only if $c_B < \frac{d_B+d_G}{d_B+2d_G(1+d_B)} + \frac{d_G(1+2d_B)}{d_B+2d_G(1+d_B)}c_G \equiv C_B^{TI}$ and $c_B > -\frac{d_B+d_G}{d_B(1+2d_G)} + \frac{d_G+2d_B(1+d_G)}{d_B(1+2d_G)}c_G \equiv C_G^{TI}$, respectively.

Figure 1 depicts the relative position of all the cutoffs identified in Subsections 4.1-4.3, which give rise to eight regions in the (c_B, c_G)-quadrant. In region I and II (VIII), the brown (green, respectively) firm is extremely inefficient relative to its rival, which leads this firm to not produce a positive output, both when regulation is absent and with either form of regulation.[15] The opposite happens in region V, where both types of firms produce a positive output under all regulatory settings. In contrast, the brown (green) firm is active under only some forms of regulation in regions

[14] Recall that environmental damages satisfy $d_B \geq d_G \geq 1/2$ throughout the paper. Otherwise, the green firm would be subject to a negative fee (receiving a subsidy per unit of output), making firms' preferences towards environmental regulation become unambiguous. Our analysis focuses, instead, on contexts where firms' preferences are more ambiguous, namely, whereby the green firm's production, while being cleaner than that of the brown firm $d_B \geq d_G$, is not substantially clean, $d_G \geq 1/2$.

[15] Graphically, the unit cost of the brown (green) firm, c_B (c_G), lies above (below) all the cutoffs for this firm, C_B^{NR}, C_B^{TD} and C_B^{TI} (C_G^{NR}, C_G^{TD} and C_G^{TI}, respectively). As a remark, note that regions I and II are separated by cutoff C^{TI}, which identifies the (c_B, c_G)-pairs below which the type-independent fee t is positive. Hence, for the analysis of the parameter values for which the brown firm produces a positive output, regions I and II can be considered as analogous to the green firm's region VIII.

III and IV (VI and VII, respectively); as Lemma 1 analyzes next. In particular, it investigates whether the introduction of regulation forces firms to shut down their operations, which we refer to as the 'shutting-down' effect; or if, instead, regulation helps inefficient firms who did not produce in the absence of environmental policy to become active otherwise, which we refer to as the 'activating' effect. (All proofs are relegated to Appendix C.)

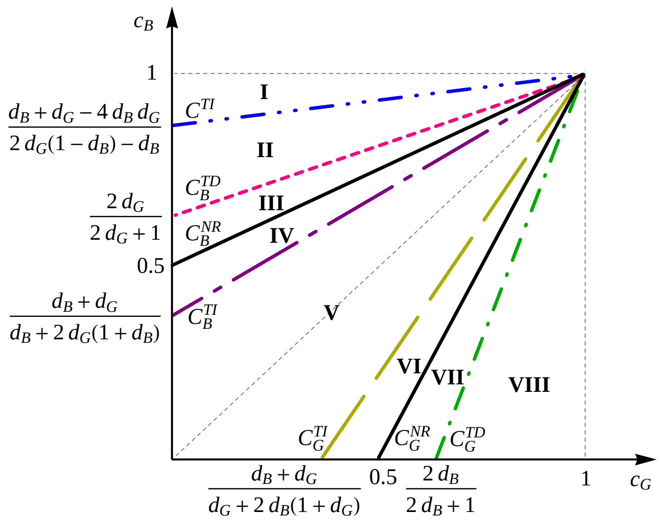


Figure 1: Relative position of the cutoffs

Lemma 1. *In region III (VII), the brown firm does not produce in the absence of regulation, but chooses a positive output under the TD policy. In contrast, in region IV (VI), the brown (green) firm produces a positive output in the absence of regulation, but shuts down under the TI policy.*

In particular, under no regulation the brown firm produces a positive output only when its cost differential is sufficiently small, i.e., when c_B lies below cutoff C_B^{NR} in Figure 1. A similar argument applies for the green firm for all cost pairs above cutoff C_G^{NR}. Importantly, the imposition of TD regulation reduces the brown firm's severe cost disadvantage in region III and thus enables it to produce a positive output (and obtain positive profits). An analogous argument applies for the green firm in region VII, whereby TD regulation would 'activate' this firm. In all regions where firms' cost differential becomes more extreme (regions I, II, and VIII), while regulation alleviates cost asymmetries, its effect is not sufficient to 'activate' the most inefficient firm. In contrast, if firms' cost differential is minor (as illustrated in regions IV-VI at the center of Figure 1), firms are active both before and after the introduction of regulation.

On the other hand, when the regulator relies on a uniform emission fees (i.e., TI fees), firms no longer benefit from regulation. Such emission fees do not reduce an inefficient firm's cost disadvantage, which, instead, remains constant before and after the introduction of regulation. As a consequence, the 'activating' effect of regulation observed with TD policies is absent and only a 'shutting-down' effect emerges. Specifically, this effect arises in region IV for the brown firm and in region VI for the green firm.

5 Profit analysis

The following proposition determines the preferences of the brown and green firm towards TD and TI regulation, when the (c_B, c_G)-pair lies in the different regions of Figure 1.

Proposition 1. *Comparing equilibrium profits under TD and TI regulation, π_K^{TD} and π_K^{TI} for every firm $K = \{B, G\}$, we obtain:*

- *The brown firm is indifferent towards the type of regulation in regions A, B, and E, i.e., $\pi_B^{TD} = \pi_B^{TI}$. In contrast, this firm supports TD (TI) regulation in region C (D, respectively), i.e., $\pi_B^{TD} > \pi_B^{TI}$.*
- *The green firm is indifferent towards the type of regulation in regions B and E, i.e., $\pi_G^{TD} = \pi_G^{TI}$. By contrast, this firm supports TD (TI) regulation in region D (A and C, respectively), i.e., $\pi_G^{TD} > \pi_G^{TI}$.*

Figure 2 depicts the preferences of the brown and green firm towards the two types of regulatory instruments. In regions A and B, the brown firm suffers such a significant cost disadvantage relative

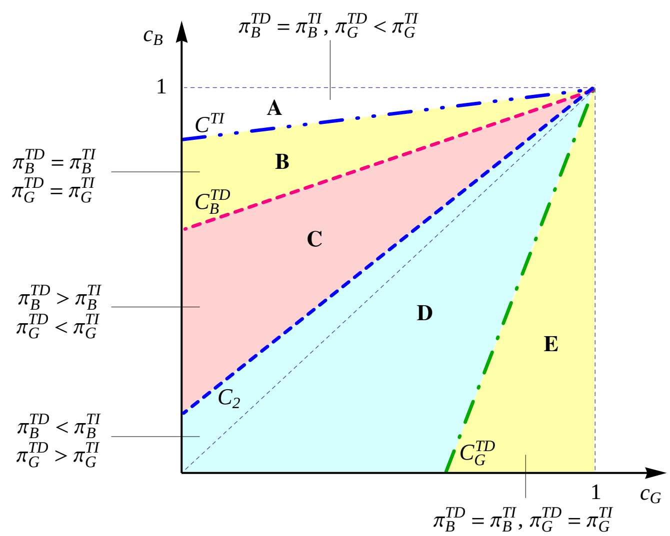


Figure 2: Firms' preferences towards TD and TI emission fees, $d_B \geq d_G \geq \frac{1}{2}$

to its green rival that it chooses to stay inactive both with and without regulation. Since the brown firm makes zero profits in these regions, regardless of the regulatory context, i.e., $\pi_B^{TD} = \pi_B^{TI} = \pi_B^{NR} = 0$, the firm is then indifferent to the policy instrument chosen by the regulator. A similar observation applies to the green firm in region E, where this firm experiences an extreme cost disadvantage relative to the brown competitor. When one of the firms is inactive under both TD and TI emission fees (regions B and E), its rival becomes indifferent to these policy instruments, as it is the only firm in the industry to be regulated.[16]

[16]Region A can be sustained as long as d_G is in the immediate neighborhood of $\frac{1}{2}$, i.e., the green firm's pollution is

Region C, whereby the brown firm prefers TD fees, encompasses area III in Figure 1 (where the firm is 'activated' by regulation), area IV, and a subset of area V, where the brown firm still suffers a cost disadvantage relative to its green rival (note that the lower bound of region C, cutoff C_2, lies above the 45°-line). Consequently, TD regulation entails a relatively lax fee on the brown firm (as it would not produce many units, and pollution, given its high costs) but a more stringent fee on its green rival due to its low production costs and, hence, larger total output. Such an asymmetric policy ameliorates the brown firm's cost disadvantage, either helping it become active or providing larger profits than under a TI policy. In contrast, the green firm prefers TI fees in this region, as a uniform fee (t) would equally harm both firms; whereas TD emission fees would subject the green firm to more stringent emission fees than the brown firm ($t_G > t_B$), and thus erode its competitive edge. The opposite argument applies to region D.[17] In particular, the relatively efficient brown firm opposes TD policy as such policy alleviates the green firm's cost disadvantage (since $t_G < t_B$) and thereby hurts the brown firm. The following corollary summarizes the main findings for regions C and D, whereby both TD and TI fees are positive.

Corollary 1. *In region C (D), equilibrium profits of the brown (green) firm are higher under the TD (TI) than under the TI (TD, respectively) policy.*

In other words, starting from a context in which regulation is absent and in which the regulator seeks to implement a TI policy, no firm will support such a regulation as it keeps the cost differential unaltered but increases costs. However, if environmental regulation is proposed, but its precise format (TD or TI) is still open for debate, one should observe that the most inefficient firm favors the introduction of policies based on the particular pollutants each firm generates, i.e., TD regulation, while efficient firms support a relatively homogeneous regulation applicable to all firms in the industry.[18]

5.1 Comparative statics

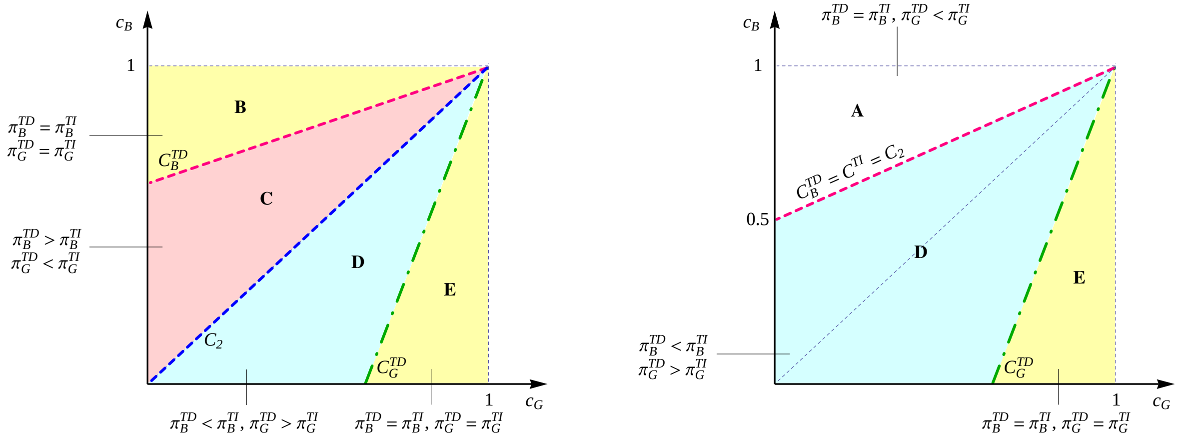
In the following corollary, we discuss how the findings presented in Proposition 1 are influenced by changes in the firms' relative environmental damages.

Corollary 2. *When firms are symmetric in their environmental damages, i.e., $d_B = d_G \geq \frac{1}{2}$, region A cannot be sustained, cutoff C_2 coincides with the 45°-line, and cutoff C_B^{TD} satisfies $C_B^{TD} = \frac{1}{C_G^{TD}}$. In contrast, if firms are highly asymmetric in their environmental damages, i.e., $d_B > d_G = \frac{1}{2}$, cutoffs satisfy $C_B^{TD} = C^{TI} = C_2$.*

not significantly damaging. Since the brown firm stays inactive in this region, due to its extreme cost disadvantage, then the green firm's pollution alone is not sufficient to induce the regulator to set a positive fee under TI regulation, i.e., $t = 0$. This implies $\pi_G^{TD} < \pi_G^{TI} = \pi_G^{NR}$.

[17] Region D embodies area VII of Figure 1, whereby the green firm is 'activated' by TD fees, as well as area VI and the subset of the area V in which the green firm exhibits a relative cost disadvantage. Therefore, the introduction of TD regulation reduces the green firm's cost disadvantage, either helping this firm become active or obtain larger profits than under a TI policy.

[18] Recall that TD and TI emission fees are both positive when the (c_B, c_G)-pair lies in region bounded by cutoffs C_B^{TD} and C_G^{TD}, i.e., areas C and D.



(a) $d_B = d_G \geq \frac{1}{2}$

(b) $d_B > d_G = \frac{1}{2}$

Figure 3: Preferences under different environmental damages

Figure 3 depicts how the cutoffs identified in Figure 2 change with respect to changes in environmental damages generated by the brown and green firms. Specifically, when the production of the brown and green firm entails symmetric damages (Figure 3a), the green firm's preferences towards TD and TI regulations become the mirror image of that of the brown firm's (above the 45°-line), since both firms do not differ with respect to their environmental footprint. Conversely, when the environmental footprint of the green firm approaches its lower bound ($d_G \to \frac{1}{2}$ as depicted in Figure 3b), cutoffs C^{TI} and C_2 converge to cutoff C_B^{TD}. In this case, the region in which only the green firm favors TD regulation (i.e., region D from Figure 2) expands, while that in which only the brown firm favors TD regulation (i.e., region C from Figure 2) disappears altogether. Intuitively, when the green firm becomes cleaner ($d_G \to \frac{1}{2}$), the regulator imposes a lax fee on this firm under the TD regime. In contrast, under TI fees, it is subject to a positive uniform fee. Therefore, the green firm supports TD regulation under larger parameter conditions (region D expands).

6 Welfare comparisons

In this section, we demonstrate that the regulator has incentives to introduce environmental regulation, regardless of the relative cleanliness of firms' production processes (i.e., $d_B \geq d_G \geq \frac{1}{2}$ or $d_B \geq \frac{1}{2} > d_G$), and that the firm-specific policy embodied in TD fees yields a weakly larger welfare than that arising under TI fees.

Lemma 2. *The social welfare is weakly larger under TD regulation than TI regulation, i.e., $SW^{TD} \geq SW^{TI}$. The introduction of TI (TD) regulation entails a weak (strict) welfare improvement, i.e., $SW^{TI} \geq SW^{NR}$ ($SW^{TD} > SW^{NR}$, respectively).*

Intuitively, although TI regulation is welfare improving (relative to no regulation at all), it entails a stringent fee on green firms and a lax fee on brown firms, relative to those arising under

TD regulation. TD fees, in contrast, avoid such a suboptimal result by setting a different fee on each firm type, thereby yielding a higher welfare relative to TI policy. Our results suggest that such welfare ranking of regulatory settings holds even when the green firm is sufficiently clean to be exempted from paying a TD emission fee (i.e., $t_G = 0$). Therefore, while regulators have incentives to introduce TD fees, our results suggest that governments can face support from different types of firms; green but also brown, depending on their relative efficiency. The following proposition examines the inefficiencies arising from setting a uniform fee under TI regulation, and thus evaluates the intensity of the regulator's preference towards TD regulation.

Proposition 2. *When the green firm is:*

a) ***Moderately Clean:*** *The minimal inefficiency between TD and TI regulation, as measured by $SW^{TD} - SW^{TI}$, occurs at cutoff $c_G = \frac{d_B - d_G}{1-d_G(1+2d_B)} + \frac{1-d_B(1+2d_G)}{1-d_G(1+2d_B)} c_B \equiv C_W$, and such inefficiency increases as c_B or c_G (or both) depart from cutoff C_W.*

b) ***Significantly Clean:*** *The minimal (maximal) inefficiency between TD and TI regulation, as measured by $SW^{TD} - SW^{TI}$, occurs at cutoff*

$$
\begin{aligned}
c_G \;=\; & \frac{d_B(1+4d_B) + d_G\{1+(1+2d_B)[d_G(8d_B-1)-7d_B]\}}{[2d_B(1-d_G)-d_G][2+2d_B(1-3d_G)-3d_G]} \\
& + \frac{3d_B + 2d_G^2(2-d_B)(1+2d_B) - d_G(1+d_B)(3+2d_B)}{[2d_B(1-d_G)-d_G][2+2d_B(1-3d_G)-3d_G]} c_B \equiv C'_W,
\end{aligned}
$$

and such inefficiency increases (decreases) as c_B or c_G (or both) depart from cutoff C'_W if $d_G > \frac{2(1+d_B)}{3(1+2d_B)}$ ($d_G \leq \frac{2(1+d_B)}{3(1+2d_B)}$, respectively).

Let us separately analyze the results in Proposition 2. First, in part (a) both firms are relatively polluting, and thus both are subject to emission fees. In this setting, the TD regulation induces socially optimal output levels, whereas the TI policy does not (as it sets a uniform fee on both firms) and leads to inefficiencies. As expected, when firms are relatively symmetric, the inefficiency from TI policy is small, but when firms become more cost asymmetric such inefficiency expands. A more unexpected finding emerges in part (b) of the proposition, whereby the green firm is sufficiently clean to be exempt from emission fees. In this context, while the TI regulation still produces inefficiencies, the TD policy can also induce the green firm to produce an output level that does not coincide with the social optimum. Specifically, for the efficient outcome to be achieved, the regulator would need to provide a negative tax (a subsidy) to the green firm, as in this setting the market failure arising from its underproduction is more significant than that emerging from its pollution. However, if the regulator is restricted to set positive or zero emission fees, this gives rise to a new form of inefficiency, only occurring under TD regulation, whereby the green firm's output is too small relative to the social optimum.[19] Ultimately, when such inefficiency is sufficiently large,

[19]Needless to say, if the regulator could provide subsidies to extremely clean green firms, the social welfare under TD would be maximal (first best), while TI policies would entail an unambiguous lower welfare.

it shrinks the social welfare under TD regulation, thus reducing the size of the inefficiency of the TI policy, as measured by $SW^{TD} - SW^{TI}$. Hence, while the TI policy is suboptimal under all parameter values (both in cases a and b), its relative size critically depends on whether the green firm is sufficiently clean to be exempt from fees, thus providing the regulator with more or less incentives to implement the policy change towards TD policy. In particular, when firms are cost asymmetric, large welfare gains can be achieved by introducing TD regulation when the green firm is moderately clean; whereas when firms are cost symmetric, TD policy is particularly beneficial when the green firm is significantly clean.

7 Policy implications and Conclusion

Unexpected supporters and opponents of a firm-specific policy. Our results suggest that, when the green firm's production entails non-negligible environmental damage, i.e., $d_B \geq d_G \geq \frac{1}{2}$, the regulator can receive political support (opposition) from an "unexpected ally" ("unexpected opponent", respectively) towards a firm-specific policy. Specifically, when brown firms endure a cost disadvantage relative to green firms, they support the introduction of TD emission fees, which helps brown firms lessen their cost disadvantage. In contrast, green firms, despite their cleaner production, oppose the introduction of TD policies; lobbying in favor of a relatively homogeneous regulation in order to keep the cost differential unchanged.

Natural supporters and opponents of a firm-specific policy. When the industry is characterized by a group of polluting and extremely clean firms, i.e., $d_B \geq \frac{1}{2} > d_G$, governments should generally anticipate a strong political support (opposition) towards the desirable goal of TD regulation from green (brown, respectively) firms. In this setting, TD policy raises the production costs of brown firms alone, hence expanding the green firm's cost advantage, which ultimately favor this policy. In contrast, brown firms prefer a less harmful TI regulation, which leaves firms' relative cost differential unaffected. Such preferences towards regulatory instruments, where the brown (green) firm favors TI (TD, respectively) regulation, can also arise when the production of green firms is not significantly clean, i.e., $d_B \geq d_G \geq \frac{1}{2}$. Specifically, when the green firm suffers a significant cost disadvantage relative to its brown rival, the inefficient green firm supports a TD regulation in order to reduce its cost disadvantage, whilst the brown firm strives to keep the cost differential unaltered by lobbying in favor of a TI regulation.

Implications of interaction of different policies. If the regulator intends to achieve the political support of green firms towards the introduction of welfare-maximizing firm-specific policy, he should create programs that provide technological and financial assistance to these firms to make their production processes significantly clean. In such cases, according to our findings, the green firms support TD policy under large parameter values. Moreover, our results indicate that, when the green firm is moderately clean, making a firm less efficient (through other non-environmental policies that affect firm's production costs) can help in its posterior support towards TD policies. By contrast, making a firm more efficient (a common goal in many government agencies) can have unintended consequences, as the affected firms would likely become opposed to a firm-specific environmental regulation.

Weighing in benefits and costs of TD regulation. From a policy perspective, regulators will compare the welfare benefits of implementing TD policy against its cost (stemming from dedicating government staff and technicians to data collection, preparation of paperwork, new administrative procedures, etc.). As suggested in Proposition 2, when firms are cost asymmetric, large welfare gains from TD regulation can arise if the green firm is not significantly clean. In such settings, welfare gains of TD policies likely exceed their implementation costs. However, when the green firm is significantly clean, the costs of implementing a TD regulation may surpass its benefits; ultimately suggesting that regulators might prefer to keep TI policies. The opposite argument applies to settings where firms are cost symmetric, whereby TD regulation is particularly beneficial when the green firm is particularly clean, but might not exceed its development costs when the green firm is not significantly clean.

Further research. Our analysis can be extended in different ways. First, we consider imperfect (Cournot) competition which characterizes competition in certain industries (e.g., airline, energy, and freight transportation). Future studies can examine how our findings are affected under other forms of market structure, such as differentiated price competition or the entry model. Second, we use per unit emission fees to regulate pollution. However, one could consider other policy instruments, such as tradable quotas, and nonlinear taxes. Furthermore, in the present study firms' production costs and emissions are assumed to be common knowledge. A natural extension is to consider a setting where each firm is privately informed its costs and/or the level of emissions. In this context, the regulator would have to use a mechanism design approach to set environmental policy, similar to that studied by Ulph (2000), in which firms are induced to truthfully report their costs.

Appendix A - Emissions and costs in different industries

Table A.1: EPA Emission Standards for Freight Transports, in grams/brake horsepower-hour

Freight Trucks			Freight Trains		
Model Year	NO_x	PM	Model Year	NO_x	PM
1974-1978	-	-	Est. 1990 Baseline Levels		
1979-1983	-	-	Line-haul duty-cycle	13.0	0.32
1984-1987	10.7	-	Switch duty-cycle	17.4	0.44
1988-1989	10.7	0.60	Tier 0 (1973-2001 model years)		
1990	6.0	0.60	Line-haul duty-cycle	9.5	0.60
1991-1993	5.0	0.25	Switch duty-cycle	14.0	0.72
1994-1997	5.0	0.10	Tier 1 (2002-2004 model years)		
1998-2003	4.0	0.10	Line-haul duty-cycle	7.4	0.45
2004-2006	2.0	0.10	Switch duty-cycle	11.0	0.54
2007+	0.2	0.01	Tier 2 (2005+ model years)		
			Line-haul duty-cycle	5.5	0.20
			Switch duty-cycle	8.1	0.24

Source: U.S. Department of Transportation (2005, p.59).
Note: NO_x = nitrogen oxides; PM = particulate matter.

Table A.2: Air Emission Factor Ranges for Freight Truck and Rail, in grams/tone-km

Pollutant	Truck	Train
CO	0.25-2.40	0.02-0.15
CO_2	127-451	41-102
HC	0.30-1.57	0.01-0.07
NO_x	1.85-5.65	0.20-1.01
SO_2	0.10-0.43	0.07-0.18
PM	0.04-0.90	0.01-0.08
VOC	1.10	0.08

Source: Organization for Economic Co-operation and Development (1997).
Note: CO = carbon monoxide; CO_2 = carbon dioxide; HC = hydrocarbons (e.g., methane, pentane, etc.); NO_x = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide; VOC = volatile organic carbon compounds.

Table A.3: Estimated Annualized Cost of Power (2008 $)

Technology	Non-Fuel Cost	Fuel Cost	SO_2 and NO_x Cost	CO_2 Cost	Production Tax Credit	Capital Return	Total Cost $/Mwh
Without Carbon Controls							
Coal: Pulverized	$5.57	$11.13	$0.61	$0.00	$0.00	$45.79	$63.10
Coal: IGCC	$5.46	$10.41	$0.10	$0.00	$0.00	$67.02	$82.99
Nuclear	$6.13	$5.29	$0.00	$0.00	($3.18)	$74.99	$83.22
With Carbon Controls							
Coal: Pulverized	$5.57	$11.13	$0.61	$33.80	$0.00	$49.58	$100.69
Coal: Pulverized/CCS	$13.48	$14.13	$0.77	$4.29	$0.00	$78.87	$111.54
Coal: IGCC	$5.46	$10.41	$0.10	$31.61	$0.00	$67.02	$114.60
Coal: IGCC/CCS	$7.10	$12.61	$0.13	$3.83	$0.00	$95.25	$118.92
Nuclear	$6.13	$5.29	$0.00	$0.00	($3.18)	$74.99	$83.22

Source: U.S. Congressional Research Service (2008).

Note: Mwh = megawatt-hour; CC = combined cycle; IGCC = integrated gasification combined cycle; CCS = carbon capture and sequestration; SO_2 = sulfur dioxide; NO_x = nitrogen oxides.

Appendix B - Significantly clean green firm

For completeness, in this section we briefly discuss how our above results are affected if environmental damages are more asymmetric, i.e., $d_B \geq \frac{1}{2} > d_G$, which allows for $d_G = 0$ as a special case, whereby the green firm is completely clean. The green firm, being significantly clean in this case, is exempt from TD emission fees, i.e., $t_G = 0$, whilst the brown firm remains subject to TD regulation, i.e., $t_B > 0$.[20] As a result, the 'activating' effect of TD regulation is absent for the brown firm. Intuitively, such effect would emerge if regulation entailed a strong amelioration of a firm's cost disadvantage. In this context, however, TD regulation does not ameliorate but actually expands the brown firm's cost disadvantage, ultimately reducing its profits. The green firm, on the other hand, can still be activated by TD regulation. Although the introduction of TI fees entails a symmetric increase in the production costs of both the brown and green firm, thus leaving their cost differential unaffected, both firms are still harmed by such regulation. In particular, such policy has a 'shutting-down' effect on the green firm's production.

In general, when green firms' production is very clean, i.e., $d_B \geq \frac{1}{2} > d_G$, relative efficiency does not play a role in determining firm's preferences towards regulation, leading green (brown) firms to lobby in favor of (against, respectively) TD fees irrespective of their cost differentials.[21] However, when green firms' production is not significantly clean, i.e., $d_B \geq d_G \geq \frac{1}{2}$, relative efficiency becomes a key determinant of firms' preferences towards regulation. In particular, as described in Corollary 1, the green firm lobbies for a firm-specific policy when it endures a significant cost disadvantage relative to the brown firm, while it opposes such regulation when it exhibits a cost advantage. An analogous finding applies to the brown firm.

When firms' environmental damages satisfy $d_B \geq \frac{1}{2} > d_G$, equilibrium output levels, emission fees, and social welfare under no regulation and TI regulation remain the same as in Section 4.1. When $d_G < \frac{1}{2}$, the green firm is exempt from the TD emission fee, i.e., $t_G = 0$, whereas the brown firm is still subject to the fee:

$$t_B = \frac{2d_B d_G(2 - c_B - c_G) - d_G(1 - 2c_B + c_G) - d_B(1 + c_B - 2c_G)}{d_B + d_G + 2d_B d_G}$$

which is positive if and only if $c_B < C^{TI}$.[22] A single policy instrument t_B, while not guaranteeing that each firm produces its socially optimal level of output, it ensures that aggregate production is efficient. The brown and green firm produce $q_B^{TD} = \frac{d_G(1-2c_B+c_G)+d_B(1-c_G)(1-2d_G)}{d_B+d_G+2d_B d_G}$ and $q_G^{TD} =$

[20] Note that if $d_G \leq d_B \leq \frac{1}{2}$, the regulator does not impose any emission fee. This is because, despite one firm still remaining relatively more polluting than another, firms' production overall entails an insignificant damage, and hence exempting them from fees.

[21] In this context brown firms actually oppose any type of regulation, but TD fees are especially profit reducing. This is because a TD policy increases the brown firm's costs while leaving those of the green firm unaffected. However, with a TI policy, both firms are subject to the same emission fee (t) and, hence, both experience a symmetric increase in their costs.

[22] Cutoff C^{TI} originates at $\frac{d_B+d_G-4d_B d_G}{2d_G(1-d_B)-d_B}$, which is positive for all $\frac{d_B}{4d_B-1} < d_G < \frac{1}{2}$ and negative for all $d_G < \frac{d_B}{4d_B-1} < \frac{1}{2}$, and lies to the left of cutoff C_G^{TI} for all $d_G < \frac{1}{2} \leq d_B$.

$\frac{[2d_B(1-c_G)+c_B-c_G]d_G}{d_B+d_G+2d_Bd_G}$, respectively, which are positive if and only if

$$c_B < \frac{d_B + d_G(1-2d_B)}{2d_G} + \frac{d_G - d_B(1-2d_G)}{2d_G}c_G \equiv \tilde{C}_B^{TD}$$

and $c_B > C_G^{TD}$, respectively. The following lemma applies the results of Lemma 1 to the setting when $d_B \geq \frac{1}{2} > d_G$ (All proofs are relegated to Appendix C).

Lemma B: *The introduction of TD (TI) policy can have activating (shutting-down, respectively) effect on the green firm. Although the brown firm is harmed by both types of regulatory instruments, neither instrument yields a shutting down effect on the firm's production.*

Figure B.1 depicts the relative positions of all the cutoffs discussed above and identifies eight regions in the (c_B, c_G)-quadrant. Since in this section only the brown firm is subject to TD emission

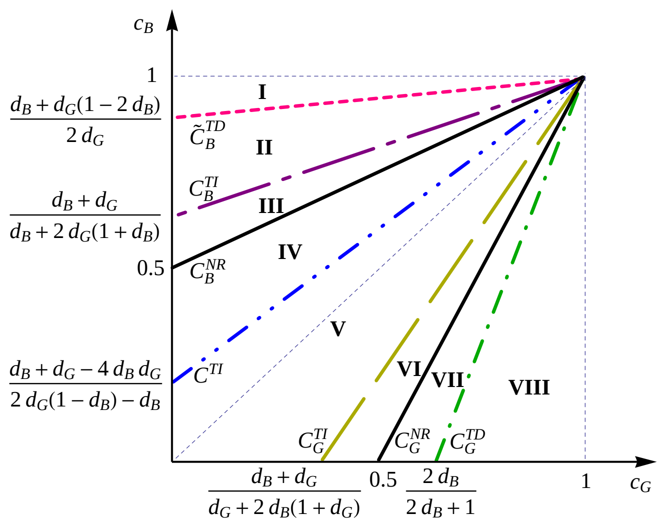


Figure B.1: Relative positions of the cutoffs

fees, the 'activating' effect of TD regulation is absent for this firm. The green firm, on the other hand, is still activated by TD regulation in region VII, where the firm's large cost disadvantage would force it to stay inactive under no regulation. The introduction of TI fees has a 'shutting-down' effect on the green firm's production in region VI, where the green firm, despite its large cost disadvantage, is able to produce a positive amount in the absence of regulation, but is forced to stay inactive when TI policy is implemented.

The following proposition determines the preferences of the brown and green firm towards TD and TI regulation, when the (c_B, c_G)-pair lies in the different regions of Figure B.1.

Proposition B: *When the green firm is significantly clean, i.e., $d_B \geq \frac{1}{2} > d_G$:*

- *In regions A' and C', both the brown and green firm are indifferent towards the type of regulation, i.e., $\pi_K^{TD} = \pi_K^{TI}$, where $K = \{B, G\}$.*

- *In contrast, in region B', the brown firm supports TI regulation, as TD regulation tends to shrink the firm's cost advantage, i.e., $\pi_B^{TD} < \pi_B^{TI}$; whereas the green firm prefers TD regulation, as it ameliorates the firm's cost disadvantage relative to the brown rival, i.e., $\pi_G^{TD} > \pi_G^{TI}$.*

In region A' of Figure B.2, which encompasses areas I-IV of Figure B.1, both firms are indifferent towards the regulatory instrument chosen by the regulator. Specifically, in regions I-III, the brown

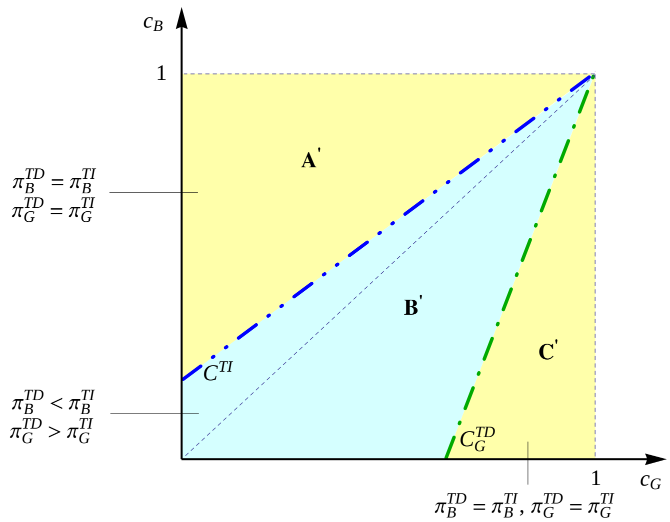


Figure B.2: Firms' preferences towards TD and TI emission fees, $d_B \geq \frac{1}{2} > d_G$

firm is at a large cost disadvantage relative to the green firm, and thus chooses to stay inactive even in the absence of regulation, i.e., $\pi_B^{NR} = \pi_B^{TD} = \pi_B^{TI} = 0$. On the other hand, the green firm faces no emission fees and no rivals, with positive profits of $\pi_G^{NR} = \pi_G^{TD} = \pi_G^{TI}$. In region IV, since TD and TI emission fees are still zero, and the brown firm's cost disadvantage is relatively small, both firms produce positive amounts and earn the same profit under all regulatory settings, i.e., $\pi_B^{TD} = \pi_B^{TI} = \pi_B^{NR}$ and $\pi_G^{TD} = \pi_G^{TI} = \pi_G^{NR}$.

In region B', which includes areas V-VII of Figure B.1, the brown firm is relatively efficient thus preferring a TI policy, whereas the inefficient green firm supports a TD policy. TD policy increases the brown firm's costs alone while leaving those of the green firm unaffected. However, with a TI policy, both firms are subject to the same emission fee (t) and, hence, both experience a symmetric increase in their costs.

Finally, in region C', which includes area VIII of Figure B.1, the green firm suffers a significant cost disadvantage relative to the brown firm and, hence, chooses to stay inactive regardless of the regulatory setting, i.e., $\pi_G^{NR} = \pi_G^{TD} = \pi_G^{TI} = 0$. On the other hand, since the brown firm is the only firm in the industry to be regulated, TD and TI emission fees coincide (i.e., $t_B = t$) and the firm becomes indifferent, i.e., $\pi_B^{TD} = \pi_B^{TI}$.

The following corollary investigates how changes in firms' environmental damages affect the findings of Proposition B.

Corollary B: *When the green firm's production becomes completely clean, i.e.,* $d_G = 0$*, the area in which the firm is indifferent between both types of regulation expands. Hence, the green firm supports* TD *regulation only when its cost disadvantage relative to the brown firm is more severe.*

When the green firm is completely clean, $d_G = 0$, cutoff C^{TI} pivots inwards, thereby expanding the region in which the firms are indifferent between both types of regulation (i.e., region A' from Figure B.2), and shrinking the region in which only the green firm favors TD emission fees (i.e., region B' from Figure B.2).

Appendix C - Proofs

Proof of Lemma 1

The 'activating' effect of TD regulation: From Figure 1, recall that in the absence of regulation the brown (green) firm produces a positive amount if and only if c_B satisfies $c_B < C_B^{NR}$ ($c_B > C_G^{NR}$). In contrast, in the presence of TD regulation, the brown (green) firm produces a positive amount if and only if c_B satisfies $c_B < C_B^{TD}$ ($c_B > C_G^{TD}$), where cutoff C_B^{TD} (C_G^{TD}) lies above (below) cutoff C_B^{NR} (C_G^{NR}) under all admissible parameter values. Since in the region between cutoffs C_B^{NR} (C_G^{NR}) and C_B^{TD} (C_G^{TD}) the brown (green) firm is enabled by TD regulation to produce a positive amount, which the firm wouldn't achieve in the absence of regulation due to large cost disadvantage, the firm is 'activated' by TD regulation.

The 'shutting-down' effect of TI regulation: From Figure 1, recall that in the presence of TI regulation the brown (green) firm produces a positive amount if and only if c_B satisfies $c_B < C_B^{TI}$ ($c_B > C_G^{TI}$), where cutoff C_B^{TI} (C_G^{TI}) lies below (above) cutoff C_B^{NR} (C_G^{NR}) under all admissible parameter values. Since in the region between cutoffs C_B^{TI} (C_G^{TI}) and C_B^{NR} (C_G^{NR}) the brown (green) firm is forced by TI regulation to stay inactive, which the firm would avoid in the absence of regulation, the firm is 'shut-down' by TI regulation. ■

Proof of Proposition 1

Given the firms' decisions regarding whether to stay active, and compete against a rival, or choose to stay inactive (as specified in the proof of Lemma 3 (Moderately Clean Green Firm)), the firms' output levels and profits corresponding to different regions in Figure 1 are discussed below.

Region I: *Brown firm:* $q_B^{NR} = q_B^{TD} = q_B^{TI} = 0 \implies \pi_B^{NR} = \pi_B^{TD} = \pi_B^{TI} = 0$. Note in this region the TI emission fee is zero, i.e., $t = 0$.
Green firm: $q_G^{TD} = \frac{1-c_G}{1+2d_G} \implies \pi_G^{TD} = \left(\frac{1-c_G}{1+2d_G}\right)^2$ and $q_G^{TI} = q_G^{NR} = \frac{1-c_G}{2} \implies \pi_G^{TI} = \pi_G^{NR} = \left(\frac{1-c_G}{2}\right)^2$, where $\pi_G^{TD} < \pi_G^{TI}$ for all $d_G > \frac{1}{2}$.

Region II: *Brown firm:* $q_B^{NR} = q_B^{TD} = q_B^{TI} = 0 \implies \pi_B^{NR} = \pi_B^{TD} = \pi_B^{TI} = 0$.
Green firm: $q_G^{NR} = \frac{1-c_G}{2} \implies \pi_G^{NR} = \left(\frac{1-c_G}{2}\right)^2$ and $q_G^{TD} = q_G^{TI} = \frac{1-c_G}{1+2d_G} \implies \pi_G^{TD} = \pi_G^{TI} = \left(\frac{1-c_G}{1+2d_G}\right)^2$.

Region III: *Brown firm:* $q_B^{NR} = q_B^{TI} = 0 \implies \pi_B^{NR} = \pi_B^{TI} = 0$ and $q_B^{TD} = \frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)} \implies \pi_B^{TD} = \left(\frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)}\right)^2$, where $\pi_B^{TD} > \pi_B^{TI} = 0$ for all parameter values.
Green firm: $q_G^{NR} = \frac{1-c_G}{2} \implies \pi_G^{NR} = \left(\frac{1-c_G}{2}\right)^2$, $q_G^{TI} = \frac{1-c_G}{1+2d_G} \implies \pi_G^{TI} = \left(\frac{1-c_G}{1+2d_G}\right)^2$, and $q_G^{TD} = \frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)} \implies \pi_G^{TD} = \left(\frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)}\right)^2$, where $\pi_G^{TD} < \pi_G^{TI}$ if and only if $C_1 < c_B < C_B^{TD}$, where

$$C_1 \equiv -1 - 4d_B + \frac{1}{1+2d_G} + \left(2 + 4d_B - \frac{1}{1+2d_G}\right) c_G$$

Cutoff C_1 originates in the negative quadrant and crosses the horizontal axis at $\frac{2[d_G+2d_B(1+2d_G)]}{1+4d_G+4d_B(1+2d_G)}$. Since region III is a subset of the area satisfying $C_1 < c_B < C_B^{TD}$, then $\pi_G^{TD} < \pi_G^{TI}$ holds for all parameter values in this region.

Region IV: The firms' preferences towards TD and TI regulation remain the same as in region III, as outputs and profits resulting from these instruments do not change. However, $q_B^{NR} = \frac{1-2c_B+c_G}{3} \implies \pi_B^{NR} = \left(\frac{1-2c_B+c_G}{3}\right)^2$ and $q_G^{NR} = \frac{1+c_B-2c_G}{3} \implies \pi_G^{NR} = \left(\frac{1+c_B-2c_G}{3}\right)^2$.

Region V: *Brown firm:* $q_B^{TD} = \frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)} \implies \pi_B^{TD} = \left(\frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)}\right)^2$, $q_B^{NR} = \frac{1-2c_B+c_G}{3} \implies \pi_B^{NR} = \left(\frac{1-2c_B+c_G}{3}\right)^2$, and $q_B^{TI} = \frac{d_G(1-2c_B+c_G)+d_B(1-c_B-2d_G(c_B-c_G))}{2(d_B+d_G+2d_Bd_G)} \implies \pi_B^{TI} = \left(\frac{d_G(1-2c_B+c_G)+d_B(1-c_B-2d_G(c_B-c_G))}{2(d_B+d_G+2d_Bd_G)}\right)^2$, where $\pi_B^{TD} > \pi_B^{TI}$ if and only if $C_2 < c_B < C_3$, where

$$
\begin{aligned}
C_2 &\equiv \frac{d_B - d_G}{d_B(1+2d_G)-1} + \frac{d_G(1+2d_B)-1}{d_B(1+2d_G)-1}c_G \\
C_3 &\equiv \frac{d_B + 3d_G}{1+d_B+2d_G(2+d_B)} + \frac{d_G(1+2d_B)+1}{1+d_B+2d_G(2+d_B)}c_G
\end{aligned}
$$

Cutoff C_2 (cutoff C_3) originates in the positive quadrant and lies below (above, respectively) cutoff C_B^{TI} under all parameter values. In particular, cutoff C_2 divides region V into two sub-regions: sub-region V$_1$ and sub-region V$_2$. The sub-region V$_1$ is a subset of the area satisfying $C_2 < c_B < C_3$, and thus profits satisfy $\pi_B^{TD} > \pi_B^{TI}$ in this region. On the other hand, the sub-region V$_2$ is not a subset of area satisfying $C_2 < c_B < C_3$, and thus the profits satisfy $\pi_B^{TD} < \pi_B^{TI}$ in this region.
Green firm: $q_G^{TD} = \frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)} \implies \pi_G^{TD} = \left(\frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)}\right)^2$, $q_G^{NR} = \frac{1+c_B-2c_G}{3} \implies \pi_G^{NR} = \left(\frac{1+c_B-2c_G}{3}\right)^2$, and $q_G^{TI} = \frac{d_G(1-c_G)+d_B(1+c_B(1+2d_G)-2c_G(1+d_G))}{2(d_B+d_G+2d_Bd_G)} \implies \pi_G^{TI} = \left(\frac{d_G(1-c_G)+d_B(1+c_B(1+2d_G)-2c_G(1+d_G))}{2(d_B+d_G+2d_Bd_G)}\right)^2$, where $\pi_G^{TD} > \pi_G^{TI}$ if and only if $C_4 < c_B < C_2$, where

$$
C_4 \equiv -\frac{3d_B + d_G}{1+d_B(1+2d_G)} + \frac{1+d_G+2d_B(2+d_G)}{1+d_B(1+2d_G)}c_G
$$

Cutoff C_4 originates in the negative quadrant and crosses the horizontal axis at $\frac{3d_B+d_G}{1+d_G+2d_B(2+d_G)}$, which lies to the right of the horizontal intercept of cutoff C_G^{TI} under all parameter values. Again, cutoff C_2 divides region V into two sub-regions: sub-region V$'_1$ and sub-region V$'_2$. The sub-region V$'_1$ is a subset of the area satisfying $C_4 < c_B < C_2$, and thus profits satisfy $\pi_G^{TD} > \pi_G^{TI}$ in this region. On the other hand, the sub-region V$'_2$ is not a subset of area satisfying $C_4 < c_B < C_2$, and hence the profits satisfy $\pi_G^{TD} < \pi_G^{TI}$ in this region.

Region VI: *Brown firm:* $q_B^{TD} = \frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)} \implies \pi_B^{TD} = \left(\frac{2d_G(1-c_B)-c_B+c_G}{2(d_B+d_G+2d_Bd_G)}\right)^2$, $q_B^{NR} = \frac{1-2c_B+c_G}{3} \implies \pi_B^{NR} = \left(\frac{1-2c_B+c_G}{3}\right)^2$, and $q_B^{TI} = \frac{1-c_B}{1+2d_B} \implies \pi_B^{TI} = \left(\frac{1-c_B}{1+2d_B}\right)^2$, where $\pi_B^{TD} < \pi_B^{TI}$ if and only if $C_G^{TD} < c_B < C_5$, where

$$
C_5 \equiv \frac{2(d_B + 2d_G + 4d_Bd_G)}{1+4(d_B+d_G+2d_Bd_G)} + \frac{1+2d_B}{1+4(d_B+d_G+2d_Bd_G)}c_G
$$

Cutoff C_5 originates at $\frac{2(d_B+2d_G+4d_Bd_G)}{1+4(d_B+d_G+2d_Bd_G)}$, which is positive and lies above the vertical intercept of cutoff C_G^{TI} under all admissible parameter values. Since region VI is a subset of the area satisfying $C_G^{TD} < c_B < C_5$, then $\pi_B^{TD} < \pi_B^{TI}$ holds for all parameter values in this region.
Green firm: $q_G^{TD} = \frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)} \implies \pi_G^{TD} = \left(\frac{2d_B(1-c_G)+c_B-c_G}{2(d_B+d_G+2d_Bd_G)}\right)^2$, $q_G^{NR} = \frac{1+c_B-2c_G}{3} \implies \pi_G^{NR} = \left(\frac{1+c_B-2c_G}{3}\right)^2$, and $q_G^{TI} = 0 \implies \pi_G^{TI} = 0$, where $\pi_G^{TD} > \pi_G^{TI} = 0$.

Region VII: The firms' preferences towards TD and TI regulation remain the same as in region VI, as outputs and profits resulting from these instruments do not change. However, $q_B^{NR} = \frac{1-c_B}{2} \implies \pi_B^{NR} = \left(\frac{1-c_B}{2}\right)^2$ and $q_G^{NR} = 0 \implies \pi_G^{NR} = 0$.

Region VIII: *Brown firm:* $q_B^{NR} = \frac{1-c_B}{2} \implies \pi_B^{NR} = \left(\frac{1-c_B}{2}\right)^2$ and $q_B^{TI} = q_B^{TD} = \frac{1-c_B}{1+2d_B} \implies \pi_B^{TI} = \pi_B^{TD} = \left(\frac{1-c_B}{1+2d_B}\right)^2$.
Green firm: $q_G^{NR} = q_G^{TI} = q_G^{TD} = 0 \implies \pi_G^{NR} = \pi_G^{TI} = \pi_G^{TD} = 0$. ■

Proof of Corollary 2

Symmetric damages, $d_B = d_G \geq \frac{1}{2}$: In this setting, the four relevant cutoffs depicted in Figure 2 become $C^{TI} = 2 - c_G$, $C_B^{TD} = \frac{2d_B+c_G}{2d_B+1}$, $C_2 = c_G$ and $C_G^{TD} = c_G(2d_B+1) - 2d_B$. Cutoff C^{TI} originates at 2 and lies entirely outside the region bounded by (c_B, c_G)-quadrant. Thus, region A from Figure 2 cannot be sustained in this setting. Cutoff C_2 now lies along the 45°-line. Cutoff C_B^{TD} originates at $\frac{2d_B}{2d_B+1}$ and is increasing in c_B. Cutoff C_G^{TD} originates in the negative quadrant, crosses the horizontal axis at $\frac{2d_B}{2d_B+1}$, and is increasing in c_B. Hence, regions B and C are the mirror image of regions D and E, respectively.

Cleanest green firm, $d_B > d_G = \frac{1}{2}$: In this setting, the four cutoffs depicted in Figure 2 become $C_B^{TD} = C^{TI} = C_2 = \frac{1+c_B}{2}$ and $C_G^{TD} = c_G(2d_B+1) - 2d_B$. Since cutoff C^{TI} pivots downward (until coinciding with cutoff C_B^{TD}) and cutoff C_2 pivots upwards (until coinciding with cutoff C_B^{TD} too), then regions A and D expand at the expense of regions B and C, respectively. Since cutoff C_G^{TD} is not a function of d_G, then region E remains unaffected. ■

Proof of Lemma B

Brown firm: From Figure B.1, recall that in the absence of regulation the brown firm produces a positive amount if and only if c_B is sufficiently low, i.e., $c_B < C_B^{NR}$. In contrast, in the presence of TD (TI) regulation the brown firm produces a positive amount if and only if c_B satisfies $c_B < \tilde{C}_B^{TD}$ ($c_B < C_B^{TI}$), where the emission fee t_B (t, respectively) is positive if and only if $c_B < C^{TI}$. Notice that cutoff C^{TI} lies below cutoff C_B^{NR}, while cutoffs $\tilde{C}_B^{TD}$ and C_B^{TI} both lie above that cutoff under all admissible parameter values. Such position of the cutoffs indicate that the brown firm is able to produce a positive amount, both with and without regulation, under all (c_B, c_G)-pairs that satisfy $c_B < C^{TI}$, i.e., $t > 0$ and $t_B > 0$. Besides, the area satisfying $c_B < C^{TI}$ is a subset of region satisfying $c_B < C_B^{NR}$. Therefore, neither TD nor TI regulation entail a 'shutting-down' effect on brown firm.

Green firm: Since the relative position of cutoffs C_G^{TI}, C_G^{NR}, and C_G^{TD} do not change from

Figure 1 to Figure B.1, we refer the reader to the proof of Lemma 1 for the discussion of 'activating' ('shutting-down') effect of TD (TI, respectively) regulation on the green firm's production. ■

Proof of Proposition B

Given the firms' output levels in the proof of Lemma 3 (Significantly Clean Green Firm), which correspond to different regulatory settings and different regions of Figure B.1, we next compare the profits arising under TD and TI regulation.

Regions I-III: *Brown firm:* $q_B^{NR} = q_B^{TD} = q_B^{TI} = 0 \implies \pi_B^{NR} = \pi_B^{TD} = \pi_B^{TI} = 0$. Note in these regions emission fees are zero, i.e., $t_B = 0$ and $t = 0$.
Green firm: $q_G^{NR} = q_G^{TD} = q_G^{TI} = \frac{1-c_G}{2} \implies \pi_G^{NR} = \pi_G^{TD} = \pi_G^{TI} = \left(\frac{1-c_G}{2}\right)^2$.

Region IV: *Brown firm:* $q_B^{NR} = q_B^{TD} = q_B^{TI} = \frac{1-2c_B+c_G}{3} \implies \pi_B^{NR} = \pi_B^{TD} = \pi_B^{TI} = \left(\frac{1-2c_B+c_G}{3}\right)^2$. Note in this region emission fees are zero, i.e., $t_B = 0$ and $t = 0$.
Green firm: $q_G^{NR} = q_G^{TD} = q_G^{TI} = \frac{1+c_B-2c_G}{3} \implies \pi_G^{NR} = \pi_G^{TD} = \pi_G^{TI} = \left(\frac{1+c_B-2c_G}{3}\right)^2$.

Region V: *Brown firm:* $q_B^{NR} = \frac{1-2c_B+c_G}{3} \implies \pi_B^{NR} = \left(\frac{1-2c_B+c_G}{3}\right)^2$, $q_B^{TD} = \frac{d_G(1-2c_B+c_G)+d_B(1-c_G)(1-2d_G)}{d_B+d_G+2d_Bd_G} \implies \pi_B^{TD} = \left(\frac{d_G(1-2c_B+c_G)+d_B(1-c_G)(1-2d_G)}{d_B+d_G+2d_Bd_G}\right)^2$, and $q_B^{TI} = \frac{d_G(1-2c_B+c_G)+d_B(1-c_B-2d_G(c_B-c_G))}{2(d_B+d_G+2d_Bd_G)} \implies \pi_B^{TI} = \left(\frac{d_G(1-2c_B+c_G)+d_B(1-c_B-2d_G(c_B-c_G))}{2(d_B+d_G+2d_Bd_G)}\right)^2$, where $\pi_B^{TD} > \pi_B^{TI}$ if and only if $C^{TI} < c_B < C_6$, where

$$C_6 \equiv \frac{d_B(3-4d_G)+3d_G}{d_B+2d_G(3+d_B)} + \frac{3d_G-2d_B(1-3d_G)}{d_B+2d_G(3+d_B)}c_G$$

Cutoff C_6 originates at $\frac{d_B(3-4d_G)+3d_G}{d_B+2d_G(3+d_B)}$, which is positive and lies above the vertical intercept of cutoff C^{TI} for all $d_B \geq \frac{1}{2} > d_G$. Since region V is not a subset of the area satisfying $C^{TI} < c_B < C_6$, then $\pi_B^{TD} > \pi_B^{TI}$ cannot be sustained in this region. Hence, $\pi_B^{TD} < \pi_B^{TI}$.
Green firm: $q_G^{NR} = \frac{1+c_B-2c_G}{3} \implies \pi_G^{NR} = \left(\frac{1+c_B-2c_G}{3}\right)^2$, $q_G^{TD} = \frac{[2d_B(1-c_G)+c_B-c_G]d_G}{d_B+d_G+2d_Bd_G} \implies \pi_G^{TD} = \left(\frac{[2d_B(1-c_G)+c_B-c_G]d_G}{d_B+d_G+2d_Bd_G}\right)^2$, and $q_G^{TI} = \frac{d_G(1-c_G)+d_B(1+c_B(1+2d_G)-2c_G(1+d_G))}{2(d_B+d_G+2d_Bd_G)} \implies \pi_G^{TI} = \left(\frac{d_G(1-c_G)+d_B(1+c_B(1+2d_G)-2c_G(1+d_G))}{2(d_B+d_G+2d_Bd_G)}\right)^2$, where $\pi_G^{TD} > \pi_G^{TI}$ if and only if $C_7 < c_B < C^{TI}$, where

$$C_7 \equiv -\frac{d_B+d_G+4d_Bd_G}{d_B+2d_G(1+d_B)} + \frac{3d_G+2d_B(1+3d_G)}{d_B+2d_G(1+d_B)}c_G$$

Cutoff C_7 originates in the negative quadrant and crosses the horizontal axis at $\frac{d_B+d_G+4d_Bd_G}{2d_B+3d_G(1+2d_B)}$, which lies to the right of the horizontal intercept of cutoff C_G^{TI} under all admissible parameter values. Since region V is a subset of the area satisfying $C_7 < c_B < C^{TI}$, then $\pi_G^{TD} > \pi_G^{TI}$ holds in this region.

Region VI: *Brown firm:* $q_B^{NR} = \frac{1-2c_B+c_G}{3} \implies \pi_B^{NR} = \left(\frac{1-2c_B+c_G}{3}\right)^2$, $q_B^{TD} = \frac{d_G(1-2c_B+c_G)+d_B(1-c_G)(1-2d_G)}{d_B+d_G+2d_Bd_G} \implies \pi_B^{TD} = \left(\frac{d_G(1-2c_B+c_G)+d_B(1-c_G)(1-2d_G)}{d_B+d_G+2d_Bd_G}\right)^2$, and $q_B^{TI} = \frac{1-c_B}{1+2d_B} \implies$

$\pi_B^{TI} = \left(\frac{1-c_B}{1+2d_B}\right)^2$, where $\pi_B^{TD} < \pi_B^{TI}$ if and only if $C_G^{TD} < c_B < C_8$, where

$$C_8 \equiv \frac{2(d_G + d_B(1 + d_B + d_G(1 - 2d_B)))}{d_B + 3d_G(1 + 2d_B)} + \frac{(1 + 2d_B)(d_G - d_B(1 - 2d_G))}{d_B + 3d_G(1 + 2d_B)} c_G$$

Cutoff C_8 originates at $\frac{2(d_G+d_B(1+d_B+d_G(1-2d_B)))}{d_B+3d_G(1+2d_B)}$, which is positive for all $d_B \geq \frac{1}{2} > d_G$. Since region VI is a subset of the area satisfying $C_G^{TD} < c_B < C_8$, then $\pi_B^{TD} < \pi_B^{TI}$ holds in this region. *Green firm:* $q_G^{NR} = \frac{1+c_B-2c_G}{3} \implies \pi_G^{NR} = \left(\frac{1+c_B-2c_G}{3}\right)^2$, $q_G^{TD} = \frac{[2d_B(1-c_G)+c_B-c_G]d_G}{d_B+d_G+2d_B d_G} \implies \pi_G^{TD} = \left(\frac{[2d_B(1-c_G)+c_B-c_G]d_G}{d_B+d_G+2d_B d_G}\right)^2$, and $q_G^{TI} = 0 \implies \pi_G^{TI} = 0$, where $\pi_G^{TD} > \pi_G^{TI} = 0$.

Region VII: The firms' preferences towards TD and TI regulation remain the same as in region VI, as outputs and profits resulting from these instruments do not change. However, $q_B^{NR} = \frac{1-c_B}{2} \implies \pi_B^{NR} = \left(\frac{1-c_B}{2}\right)^2$ and $q_G^{NR} = 0 \implies \pi_G^{NR} = 0$.

Region VIII: *Brown firm:* $q_B^{NR} = \frac{1-c_B}{2} \implies \pi_B^{NR} = \left(\frac{1-c_B}{2}\right)^2$ and $q_B^{TD} = q_B^{TI} = \frac{1-c_B}{1+2d_B} \implies \pi_B^{TD} = \pi_B^{TI} = \left(\frac{1-c_B}{1+2d_B}\right)^2$.
Green firm: $q_G^{NR} = q_G^{TD} = q_G^{TI} = 0 \implies \pi_G^{NR} = \pi_G^{TD} = \pi_G^{TI} = 0$. ■

Proof of Corollary B

Extremely clean green firm, $d_G = 0$: In this setting, cutoff C^{TI} depicted in Figure B.2 becomes $C^{TI} = 2c_G - 1$, which originates in the negative quadrant and crosses the horizontal axis at $\frac{1}{2}$. Since cutoff C^{TI} pivots downward, then region A' expands at the expense of shrinking of region B'. In contrast, region C' remains unaffected as cutoff C_G^{TD} is not a function of d_G. ■

Proof of Lemma 3

Moderately clean green firm

We calculate the social welfare arising in the presence (TD and TI) and absence of regulation when firms' costs lie in eight different regions as identified in Figure 1. Subsequently, we rank the policies according to their welfare implications.

Region I: The brown firm is extremely inefficient relative to its green rival so that the firm is forced to stay inactive both with and without regulation, i.e., $q_B^{NR} = q_B^{TD} = q_B^{TI} = 0$. Meanwhile, the green firm operates like a monopolist, producing $q_G^{NR} = \frac{1-c_G}{2}$ without regulation and $q_G^{TD} = \frac{1-c_G}{1+2d_G}$ with TD emission fees, i.e., $t_G = \frac{(1-c_G)(2d_G-1)}{1+2d_G}$. Under TD emission standards, the social welfare is $SW^{TD} = \frac{(1-c_G)^2}{2(1+2d_G)}$. Since $t = 0$, the social welfare under TI fees is the same as that arising under no regulation, i.e., $SW^{TI} = SW^{NR} = \frac{(3-2d_G)(1-c_G)^2}{8}$. Comparing SW^{TD} to SW^{TI}, we can show that $SW^{TD} > SW^{TI} = SW^{NR}$ holds under all parameter conditions.

Region II: The brown firm's cost disadvantage is sufficiently significant to keep the firm inactive both in the presence and absence of regulation, i.e., $q_B^{NR} = q_B^{TD} = q_B^{TI} = 0$. Since the green firm is the only firm producing positive amount in the industry, the TD and TI emission fees coincide, i.e., $t_G = t > 0$. Specifically, the regulator imposes $t_G = t = \frac{(1-c_G)(2d_G-1)}{1+2d_G}$, which induces the green firm to produce $q_G^{TD} = q_G^{TI} = \frac{1-c_G}{1+2d_G}$, thereby generating $SW^{TD} = SW^{TI} = \frac{(1-c_G)^2}{2(1+2d_G)}$. The social welfare in the absence of regulation is the same as in region I. Thus, in region II, $SW^{TD} = SW^{TI} > SW^{NR}$ holds under all parameter conditions.

Region III: The brown firm's inefficiency relative to the green rival does not allow the firm to produce positive amount both in the absence of regulation and presence of TI emission fees, i.e., $q_B^{NR} = q_B^{TI} = 0$. Thus, in these settings, the output level of the green firm and the resulting social welfare are the same as in region II. However, with TD regulation ($t_B > 0$, $t_G > 0$), the brown firm becomes active, i.e., $q_B^{TD} > 0$, and faces its green rival. Consequently, the social welfare under TD regulation is $SW^{TD} = \frac{c_G[c_G-2d_B(2-c_G)]+2(d_B+d_G)+c_B^2(1+2d_G)-2c_B(c_G+2d_G)}{4(d_B+d_G+2d_Bd_G)}$, where $SW^{TD} > SW^{TI} > SW^{NR}$ holds for all parameter values.

Region IV: Firms' output levels and social welfare corresponding to TD and TI fees are the same as in region III. However, in the absence of regulation, the brown firm is now able to compete with its green competitor, i.e., $q_B^{NR} > 0$. Hence, the social welfare under this setting is $SW^{NR} = \frac{1}{18}\{c_B^2(11 - 8d_B - 2d_G) + 2(4 - d_B - d_G) - c_G[8 - 11c_G + 2d_B(2 + c_G) - 8d_G(1 - c_G)] - 2c_B[4(1 - d_B) + 2d_G + c_G(7 - 4d_B - 4d_G)]\}$, where $SW^{NR} < SW^{TD}$ under all parameter values. In addition, $SW^{NR} < SW^{TI}$ if and only if c_B satisfies $C_9 < c_B < C_{10}$, where

$$C_9 \equiv \frac{(1+2d_G)[2(2+d_G)+c_G(7-4d_G)-4d_B(1+c_G)]-3\sqrt{A}}{(1+2d_G)(11-8d_B-2d_G)}$$

$$C_{10} \equiv \frac{(1+2d_G)[2(2+d_G)+c_G(7-4d_G)-4d_B(1+c_G)]+3\sqrt{A}}{(1+2d_G)(11-8d_B-2d_G)}$$

where $A = (1-c_G)^2(1-2d_G)^2(3-2d_B)(1+2d_G)$. Cutoff C_9 originates in the positive quadrant and lies under the vertical intercept of cutoff C_B^{TI} under all parameter values. Similarly, cutoff C_{10} originates in the positive quadrant and lies above the vertical intercepts of cutoffs C_9 as well as C_B^{NR} under all parameter values. Since region IV is a subset of the area satisfying $C_9 < c_B < C_{10}$, then $SW^{NR} < SW^{TI}$ holds under all (c_B, c_G)-pairs within region IV. Thus, $SW^{TD} > SW^{TI} > SW^{NR}$ holds under all parameter values.

Region V: Since firms' costs are relatively symmetric in this region, both firms produce positive amount both in the presence and absence of environmental regulation. In particular, firms' output levels and social welfare in the absence of regulation and in the presence of TD emission fees are the same as in region IV. However, with TI emission fees, given that the brown firm can now compete with its green rival, i.e., $q_B^{TI} > 0$, the social welfare generated amounts to

$$\begin{aligned} SW^{TI} = [2(d_B + d_G + 2d_Bd_G)]^{-2}\{&d_B^2[2(1 + c_B^2 - c_G(1 - c_G) - c_B(1 + c_G)) - d_B(1 - c_B)^2]+ \\ &d_B[4 + 5d_B - 2c_G(2 + d_B)(1 + 2d_B) + c_G^2(6 + 8d_B) + c_B^2(6 + d_B(3 - 4d_B)) - c_B(4+ \\ &2c_G(4 + 3d_B) - 4d_B^2(1 + c_G))]d_G + d_G^2[2 + 5d_B + c_B^2(2 + 4d_B(2 - d_B - d_B^2)) + c_G(2+ \\ &c_G(1 + 2d_B)(2 - d_B - 2d_B^2)) - 2c_B(1 + 5d_B + c_G(1 + d_B(3 - 4d_B(1 + d_B))))] - d_G^3[1- \\ &c_G + 2d_B(c_B - c_G)]^2\} \end{aligned}$$

Comparing SW^{TI} with SW^{TD} and SW^{NR}, it can be shown that $SW^{TI} < SW^{TD}$ holds under all parameter conditions, whereas $SW^{TI} < SW^{NR}$ holds if and only if c_B satisfies $C_{11} < c_B < C_{12}$, where

$$\begin{aligned} C_{11} &\equiv \frac{d_B[2+2d_G(3-2d_G)]+d_G(2-5d_G)-d_B^2(5+4d_G)}{d_B[4+d_G(3+10d_G)]-2d_G(1-d_G)-7d_B^2(1+2d_G)}+ \\ &\quad \frac{d_B[2+d_G(14d_G-3)]-d_G(4-7d_G)-2d_B^2(1+5d_G)}{d_B[4+d_G(3+10d_G)]-2d_G(1-d_G)-7d_B^2(1+2d_G)}c_G \\ C_{12} &\equiv \frac{d_B+d_G-4d_Bd_G}{2d_G(1-d_B)-d_B}+\frac{d_G-2d_B(1-d_G)}{2d_G(1-d_B)-d_B}c_G \end{aligned}$$

Cutoff C_{11} (cutoff C_{12}) originates in the positive quadrant and lies above the vertical intercept of cutoff C_B^{TI} (cutoff C_{11}, respectively) under all parameter values. Since region V and the area satisfying $C_{11} < c_B < C_{12}$ are disjoint, then $SW^{NR} < SW^{TI}$ holds under all (c_B, c_G)-pairs within region V. Therefore, $SW^{TD} > SW^{TI} > SW^{NR}$ is true for all parameter values.

Region VI: The green firm is inefficient relative to the brown firm such that the imposition of TI emission fees forces the green firm to shut down, i.e., $q_G^{TI} = 0$. As a result, the brown firm operates like a monopolist in this setting, facing emission fee $t = \frac{(1-c_B)(2d_B-1)}{1+2d_B}$ and producing $q_B^{TI} = \frac{1-c_B}{1+2d_B}$. The resulting social welfare is $SW^{TI} = \frac{(1-c_B)^2}{2(1+2d_B)}$. In the absence of regulation and presence of TD emission fees, firms' output levels and the social welfare are the same as in region V. Comparing SW^{TI} with SW^{TD} and SW^{NR}, we can show that $SW^{TI} < SW^{TD}$ under all parameter conditions, while $SW^{TI} > SW^{NR}$ if and only if c_B satisfies $C_{13} < c_B < C_{14}$, where

$$\begin{aligned} C_{13} &\equiv \frac{2d_G+4d_B(1+d_G)+c_G(1+2d_B)[7-4(d_B+d_G)]-5-8d_B^2-3\sqrt{B}}{2[1-d_G+d_B(7-8d_B-2d_G)]} \\ C_{14} &\equiv \frac{2d_G+4d_B(1+d_G)+c_G(1+2d_B)[7-4(d_B+d_G)]-5-8d_B^2+3\sqrt{B}}{2[1-d_G+d_B(7-8d_B-2d_G)]} \end{aligned}$$

where $B = (1-c_G)^2(1-2d_B)^2(3-2d_G)(1+2d_B)$. Cutoff C_{13} (cutoff C_{14}) originates in the negative quadrant and its horizontal intercept lies to the right (left) of cutoff C_G^{NR} (cutoff C_G^{TI}, respectively) under all parameter values. Since region VI is a subset of the area satisfying $C_{13} < c_B < C_{14}$, then $SW^{TI} > SW^{NR}$ holds under all (c_B, c_G)-pairs within region VI. Hence, $SW^{TD} > SW^{TI} > SW^{NR}$.

Region VII: The green firm's cost disadvantage increases further, and the firm becomes inactive in the absence of regulation as well, i.e., $q_G^{NR} = 0$. The efficient brown monopolist, on the other hand, produces $q_B^{NR} = \frac{1-c_B}{2}$ in this setting, generating total welfare of $SW^{NR} = \frac{(3-2d_B)(1-c_B)^2}{8}$. As for the firms' output levels and social welfare corresponding to TD and TI fees, they are the same as in region VI. Comparing SW^{NR} to SW^{TI}, we can show that $SW^{NR} < SW^{TI}$ holds under all parameter values. Thus, $SW^{TD} > SW^{TI} > SW^{NR}$.

Region VIII: The green firm is extremely inefficient relative to the brown firm, so that the firm stays inactive both with and without regulation, i.e., $q_G^{NR} = q_G^{TI} = q_G^{TD} = 0$. As a result, the brown firm operates like a monopolist, facing emission fee $t = t_B = \frac{(1-c_B)(2d_B-1)}{1+2d_B}$ and producing

$q_B^{TD} = q_B^{TI} = \frac{1-c_B}{1+2d_B}$ with regulation. The resulting social welfare is $SW^{TI} = SW^{TD} = \frac{(1-c_B)^2}{2(1+2d_B)}$. In the absence of regulation, production and social welfare are the same as in region VII. As a result, $SW^{TD} = SW^{TI} > SW^{NR}$. ■

Significantly clean green firm

Below we compute and compare the social welfare arising in the presence and absence of environmental regulation when the (c_B, c_G)-pair lies in different regions of Figure B.1.

Regions I-III: The brown firm is at significant cost disadvantage relative to the green firm, and hence the firm chooses to stay inactive regardless of the regulatory context, i.e., $q_B^{NR} = q_B^{TD} = q_B^{TI} = 0$. Besides, both TD and TI emission fees are 0 in this context, i.e., $t_B = t = 0$. On the other hand, the green monopolist produces $q_G^{NR} = q_G^{TD} = q_G^{TI} = \frac{1-c_G}{2}$, with the resulting social welfare of $SW^{NR} = SW^{TD} = SW^{TI} = \frac{(3-2d_G)(1-c_G)^2}{8}$.

Region IV: The brown firm is able to produce positive amount in the absence of regulation, i.e., $q_B^{NR} = \frac{1-2c_B+c_G}{3}$. Since the emission fees are still 0, i.e., $t_B = t = 0$, then $q_B^{TD} = q_B^{TI} = q_B^{NR}$. Consequently, the output level of the green firm becomes $q_G^{TD} = q_G^{TI} = q_G^{NR} = \frac{1+c_B-2c_G}{3}$. The resulting social welfare is $SW^{TD} = SW^{TI} = SW^{NR} = \frac{1}{18}\{c_B^2(11 - 8d_B - 2d_G) + 2(4 - d_B - d_G) - c_G[8 - 11c_G + 2d_B(2 + c_G) - 8d_G(1 - c_G)] - 2c_B[4(1 - d_B) + 2d_G + c_G(7 - 4d_B - 4d_G)]\}$.

Region V: In this region, both TD and TI emission fees are positive ($t_B > 0$, $t > 0$), and both firms produce positive amount regardless of the regulatory context (see Section **??** for emission fees and output levels). The social welfare under TD and TI regulations are

$$SW^{TD} = [\sqrt{2}(d_B + d_G + 2d_Bd_G)]^{-2}\{d_B^2(1 - c_G)[1 - 2c_B + c_G - 2d_B(1 - c_G)] + 2d_Bd_G[1+ 2c_B^2 + (c_G - 2d_B(1 - c_G))^2 - 2c_B(1 + c_G - 2d_B(1 - c_G))] + d_G^2[1 + 3c_B^2 + 2d_B + 2(1- d_B)(c_G - 2d_B(1 - c_G))^2 - c_B(2 - 4d_B + 8d_B^2 + 4c_G(1 - d_B)(1 + 2d_B))] - 2d_G^3[c_B+ 2d_B - c_G(1 + 2d_B)]^2\}$$

and

$$SW^{TI} = [2(d_B + d_G + 2d_Bd_G)]^{-2}\{d_B^2[2(1 + c_B^2 - c_G(1 - c_G) - c_B(1 + c_G)) - d_B(1 - c_B)^2]+ d_B[4 + 5d_B - 2c_G(2 + d_B)(1 + 2d_B) + c_G^2(6 + 8d_B) + c_B^2(6 + d_B(3 - 4d_B)) - c_B(4+ 2c_G(4 + 3d_B) - 4d_B^2(1 + c_G))]d_G + d_G^2[2 + 5d_B + c_B^2(2 + 4d_B(2 - d_B - d_B^2)) + c_G(2+ c_G(1 + 2d_B)(2 - d_B - 2d_B^2)) - 2c_B(1 + 5d_B + c_G(1 + d_B(3 - 4d_B(1 + d_B))))] - d_G^3[1- c_G + 2d_B(c_B - c_G)]^2\},$$

respectively, where $SW^{TD} > SW^{TI}$ if and only if c_B satisfies $C_{15} < c_B < C^{TI}$, where

$$C_{15} \equiv \frac{d_B(3 - 4d_G) - d_G}{2d_G(1 + d_B) - 2 + d_B} + \frac{3d_G - 2 - 2d_B(1 - 3d_G)}{2d_G(1 + d_B) - 2 + d_B}c_G$$

Cutoff C_{15} originates in the negative quadrant and crosses the horizontal axis at $\frac{d_G - d_B(3-4d_G)}{3d_G(1+2d_B)-2(1+d_B)}$, which lies to the right of cutoff C_G^{TI} for all $d_B \geq \frac{1}{2} > d_G$. Since region V is a subset of the area satisfying $C_{15} < c_B < C^{TI}$, then $SW^{TD} > SW^{TI}$ holds for all (c_B, c_G) pairs in this region.

The social welfare corresponding to unregulated market environment is the same as in region IV. We can show that $SW^{TI} < SW^{NR}$ if and only if c_B satisfies $C^{TI} < c_B < C_{16}$, where

$$C_{16} \equiv \frac{d_G(2-5d_G) - d_B^2(5+4d_G) + 2d_B(1+3d_G-2d_G^2)}{d_B(4+d_G(3+10d_G)) - 2d_G(1-d_G) - 7d_B^2(1+2d_G)} + \frac{d_B(2-d_G(3-14d_G)) - 2d_B^2(1+5d_G) - d_G(4-7d_G)}{d_B(4+d_G(3+10d_G)) - 2d_G(1-d_G) - 7d_B^2(1+2d_G)} c_G$$

Cutoff C_{16} originates in the positive quadrant and lies above cutoff C^{TI} for all $d_B \geq \frac{1}{2} > d_G$. Since region V is not a subset of the area satisfying $C^{TI} < c_B < C_{16}$, then $SW^{TI} < SW^{NR}$ cannot be sustained in this region. Hence, $SW^{TD} > SW^{TI} > SW^{NR}$, where $SW^{TD} > SW^{NR}$ holds by transitivity.

Region VI: The social welfare corresponding to TD and no regulation remain the same as in region V. Under TI regulation, however, inefficient green firm now chooses to stay inactive, i.e., $q_G^{TI} = 0$, and the monopolist brown firm produces $q_B^{TI} = \frac{1-c_B}{1+2d_B}$, facing emission fee $t = \frac{(1-c_B)(2d_B-1)}{1+2d_B}$. The resulting social welfare is $SW^{TI} = \frac{(1-c_B)^2}{2(1+2d_B)}$, where $SW^{TI} < SW^{TD}$ for all $d_B \geq \frac{1}{2} > d_G$. Also, $SW^{TI} > SW^{NR}$ (see the proof of Lemma 3 (Moderately Clean Green Firm, region VI)).

Region VII: The green firm suffers a significant cost disadvantage relative to the brown firm, and thus is forced to stay inactive in the absence of regulation, i.e., $q_G^{NR} = 0$, whilst the brown firm operates like a monopolist producing $q_B^{NR} = \frac{1-c_B}{2}$, with the resulting social welfare of $SW^{NR} = \frac{(3-2d_B)(1-c_B)^2}{8}$. Output levels, emission fees, and social welfare under TD and TI regulation remain the same as in region VI. It can be shown that $SW^{NR} < SW^{TI}$ holds for all admissible parameter values, and by transitivity $SW^{NR} < SW^{TD}$.

Region VIII: In this region, even the 'activating' effect of TD regulation is not able to keep the green firm active, i.e., $q_G^{TD} = q_G^{TI} = q_G^{NR} = 0$. Thus, the monopolist brown firm produces $q_B^{TD} = q_B^{TI} = \frac{1-c_B}{1+2d_B}$, with the resulting social welfare of $SW^{TD} = SW^{TI} = \frac{(1-c_B)^2}{2(1+2d_B)}$. Output levels, emission fees, and social welfare under no regulation remain the same as in region VII, where $SW^{NR} < SW^{TD} = SW^{TI}$. ■

Proof of Proposition 2

Moderately clean green firm

To determine how the extent of firms' relative efficiency influences the welfare gain of moving from TI to TD regulation, we start from the setting where firms' costs are symmetric and where both firms remain active under both TD and TI regulation (i.e., region V from Figure 1). See the proof of Lemma 3 (Moderately Clean Green Firm, region V) for SW^{TD} and SW^{TI}. It can be shown that

$$SW^{TD} - SW^{TI} = \frac{(d_B + d_G)[d_B - d_G + c_B(1 - d_B - 2d_B d_G) - c_G(1 - d_G - 2d_B d_G)]^2}{4(d_B + d_G + 2d_B d_G)^2}$$

where

$$\frac{\partial^2(SW^{TD} - SW^{TI})}{\partial c_G^2} = \frac{(d_B + d_G)(1 - d_G - 2d_B d_G)^2}{2(d_B + d_G + 2d_B d_G)^2} > 0$$

Thus, the difference $SW^{TD} - SW^{TI}$ is convex for all parameter values, with the minimum of the difference occurring at

$$c_G = \frac{d_B - d_G}{1 - d_G(1 + 2d_B)} + \frac{1 - d_B(1 + 2d_G)}{1 - d_G(1 + 2d_B)} c_B \equiv C_W$$

which is a nearby point to the 45°-line. By convexity in c_G, we can claim that, as we depart from the minimum point of the difference $SW^{TD} - SW^{TI}$ (i.e., getting closer to either $c_G = 0$ or $c_G = 1$), the efficiency loss of TI regulation increases.

Significantly clean green firm

Similarly, we start from the setting where firms' costs are symmetric and where both firms remain active regardless of the regulatory context (i.e., region V from Figure B.1). See the proof of Lemma 3 (Significantly Clean Green Firm, region V) for SW^{TD} and SW^{TI}. We can show that

$$\begin{aligned} SW^{TD} - SW^{TI} = {} & [2(d_B + d_G + 2d_B d_G)]^{-2}(d_B + d_G)[d_G(1 - 2c_B + c_G) + d_B(1 + c_B - \\ & 2c_G - 2d_G(2 - c_B - c_G))][d_G(1 + 4d_B) - 3d_B + c_G(2 + 2d_B - 3d_G - \\ & 6d_B d_G) - c_B(2 - d_B - 2d_G(1 + d_B))] \end{aligned}$$

where

$$\frac{\partial^2(SW^{TD} - SW^{TI})}{\partial c_G^2} = \frac{(d_B + d_G)[2d_B(1 - d_G) - d_G][-2 + 3d_G + d_B(-2 + 6d_G)]}{2(d_B + d_G + 2d_B d_G)^2}$$

which is positive (negative) if and only if $d_G > \frac{2(1+d_B)}{3(1+2d_B)}$ ($d_G < \frac{2(1+d_B)}{3(1+2d_B)}$, respectively). We can further show that $\frac{2(1+d_B)}{3(1+2d_B)} = 0.5$ when $d_B = 0.5$ and $\frac{2(1+d_B)}{3(1+2d_B)} = 0.44$ when $d_B = 1$. Since in this section $d_B \geq \frac{1}{2} > d_G$, the difference $SW^{TD} - SW^{TI}$ can be convex only when the green firm's environmental damage approaches its upper bound, i.e., $d_G >> 0.44$. Otherwise, it is concave under larger parameter conditions. The difference $SW^{TD} - SW^{TI}$ achieves its extremum when

$c_G = C'_W$, where

$$C'_W \equiv \frac{d_B(1+4d_B) + d_G\{1+(1+2d_B)[d_G(8d_B-1)-7d_B]\}}{[2d_B(1-d_G)-d_G][2+2d_B(1-3d_G)-3d_G]} + \frac{3d_B + 2d_G^2(2-d_B)(1+2d_B) - d_G(1+d_B)(3+2d_B)}{[2d_B(1-d_G)-d_G][2+2d_B(1-3d_G)-3d_G]} c_B$$

When $d_G > \frac{2(1+d_B)}{3(1+2d_B)}$ ($d_G < \frac{2(1+d_B)}{3(1+2d_B)}$), by convexity (concavity) in c_G, any departure from the extremum point of $SW^{TD} - SW^{TI}$ increases (decreases, respectively) the efficiency loss of TI regulation relative to TD regulation. ■

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