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Optimal Allocation of Tradable Pollution Rights and Market Structures*

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Abstract
Tradable environmental rights are increasingly pursed as a regulatory instrument, to control for environmental quality. However, in the presence of market power, regulation through an allocation of tradable rights generally yield inef cient outcomes. This article analyzes the effect of the initial distribution of tradable rights on the rms' strategies and performance in abatement and production, and proposes an ef cient criterion for the allocation of tradable rights among rms with market power and competitive fringe rms. The suggested criterion maximizes ef ciency of the market based regulation. A simple numerical example illustrates the theoretical discussion.

Key words: Tradable pollution rights, allocation efficiency, environmental policy

JEL Classification Codes: L130, Q580, Q520

1. Introduction

The distribution of tradable rights appears to be one of the most important components in achieving efficient market-based policies that control the consumption of non-excludable goods. The presence of market power in the market for rights and/or in related product markets may give rise to manipulative strategies intended to increase the share and profit of the dominant firm. Such strategies are liable to decrease the efficiency of market-based policies, and thus, the use of such strategies by dominant polluting firms that operate in markets for pollution rights has been drawing increasing attention. Examples include the concerns regarding the efficiency of the deregulated energy markets in the United States and the adoption of a tradable permit system to regulate the industry's sulfur dioxide emissions

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(Joskow and Schmalensee 1998; Stavins 1998; Schmalensee et al. 1998).[1] Efficiency of the electricity markets depends, to a large extent, on the presence of market power in this market and in the one for rights to pollute, and on the initial allocation of these rights among the agents.[2] Similarly, the success of a market-based approach toward airport congestion problems, where in most cases a handful of airlines dominate the market (Brueckner 2002) would largely depend on the initial distribution of rights among airlines. The same concerns have been voiced about the use of emission rights to control sulfur dioxide emissions in the UK electricity industry (von de Fehr 1993). Use of permits for exclusionary purposes was also one of the main causes preventing implementation of tradable fishing rights on the Norwegian coastline (von de Fehr 1993), and for the control of water pollution in Scotland's Fourth Estuary (Hanley and Moffat 1992).

The expanding literature on the efficiency of market-based policies focused mainly on the implications of strategic behavior on trade in environmental rights and on the equilibrium in the related markets, (Misiolek and Elder 1989; von de Fehr 1993; Fershtman and de Zeeuw 1995; Sartzetakis 1997; Joskow and Tirole 2000; Mansur 2004). Some of these studies have also illuminated advantages and disadvantages of allocating rights to firms with market power (Hahn 1984; Malueg 1990; Joskow 2000). However, the effect of the initial allocation of rights on the strategic behavior of firms in the product market and in the market for rights has not been fully developed. Consequently, the optimal approach for allocating rights in such systems is yet unclear.

The present paper focuses on the consequences of distributing tradable environmental rights among competitive and non-competitive firms, given that all rights are allocated for free. The paper adds to the literature in environmental economics by analyzing the effect of the distribution of rights on the conduct and performance of polluting firms. Furthermore, it explains the link between the initial allocation of tradable rights and the firm's ability to implement manipulative cost-raising strategies. In the field of regulatory economics, the paper identifies criteria determining an optimal allocation of rights among competitive and non-competitive agents. The suggested criteria for allocation outlines optimal market structures, which are pivotal for designing new markets for rights and evaluating efficiency of existing markets.

Section 2 outlines the theoretical framework for trade in rights and in related product markets, assuming the presence of market power in both. Section 3 models the firms' optimal strategies and analyzes the effect of the initial allocation of

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1 Although electricity prices in about half the states in the United States are still regulated, the long-term trend is towards a fully deregulated market. This creates increasing concerns regarding the efficiency of the future electricity market in the US.

2 Borenstein et al. (2002) estimated monopoly power among local electric utilities in California. Their study indicates that during periods of peak demand, the capacity constraints of fringe suppliers can create market power for a dominant firm. A significant departure from competitive pricing during the high-demand summer months was observed. Fifty nine percent of the price mark-up was attributed to market power.

rights on the strategies of the dominant firm and competitive fringe firms. Section 4 analyzes the efficiency consequences of trade under market-based regulation, with a focus on the ability to increase efficiency by redistributing rights among the agents. The efficiency analysis in this section establishes the intuition for optimal allocation criteria . The optimal criterion for allocation of rights, where all related markets are non-competitive, is derived in section 5. This section also includes a discussion of the optimal allocation of rights in other market-structures, which can be seen as special cases of the analyzed system. Section 6 illustrates the theoretical discussion with a simple numerical example, and section 7 concludes with policy implications.

2. The Framework

To analyze equilibria under different market structures, it is useful to begin by considering a system of imperfectly competitive markets, in which market power is present both in the market for rights and in the product market. The present study focuses on a system of imperfectly competitive markets in which a dominant firm (denoted by subcase letter d) and a fringe of competitive firms (denoted by subcase letter f) produce a product which generates emissions as a byproduct.[3]

The firms may either abate the generated emissions or be involved in a market for rights to pollute. The market for rights is regulated by a social planner, who determines an allocation ($\boldsymbol{\alpha}$) of rights. $\boldsymbol{\alpha}$ is the vector of shares, $\boldsymbol{\alpha} = \{\alpha_d, 1-\alpha_d\}$, where α_d stands for the share of rights allocated to the dominant firm.[4] The aggregate volume of rights allocated to the firms is fixed, and is given by R.[5] The firms can emit part or all of the emissions generated only if they hold an equivalent amount of pollution rights, x_j, and the rest need to be abated.

The dominant firm is assumed to dominate both the market for rights and the product market, and sets the prices p and t for pollution rights and output, respectively. The source of dominance of the firm type d is attributed to its superior abatement technology.[6]

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3 The setup of a dominant firm - competitive fringe firms model was also adopted in previous studies (Misiolek and Elder 1989) and reflects some existing tradable rights frameworks, as the RECLAIM program for trade in NO_x in the Los-Angeles area in which dominant and competitive fringe firms trade in the pollution rights market. The choice of such a framework in this work enables us to analyze the impact of the allocation mode on different types of agents, including price setters and price takers, all at once.

4 The allocation of rights among the competitive agents has no efficiency implications in such a market structure, and thus attention is restricted to the allocation of rights between the dominant firm and the group of fringe-competitive firms (Montgomery 1972).

5 Given the outlined framework, in which only polluting firms trade in rights, the regulator's decisions about the aggregate volume of rights and the allocation can be analyzed independently (Eshel 2004). In this paper I restrict attention only to the regulator's allocation decision.

6 Based on recent econometric studies, the adoption of the advanced technology by electric plants (adoption of scrubbers technology) requires high initial capital investment and is positively correlated with prior experience, location and ownership. Thus, it is likely that firms who dominate the output market have adopted advanced abatement technologies (Keohane 2003).

The firms' marginal abatement costs are determined by the abatement technology chosen by the firm and by the rate of pollution. To reduce marginal costs, the firm can improve its technology or reduce its emissions rate. These are complementary strategies used by the firm. For simplicity, we assume that the firms use different abatement technologies, but have the same rate of pollution. Commonly, marginal abatement cost increases with the volume of abatement and decreases with the selection of an advanced abatement technology (Keohane 2003).[7] Let the function $g_j[a_j]$ represent the variable abatement cost for agent type j as a function of the quantity abated a_j. It is assumed that $g'_j[a_j] > 0$ and $g''_j[a_j] \geq 0$ for $j = f, d$. In addition, it is assumed that dominance in the market for rights implies that $g'_d[\tilde{a}] \leq g'_f[\tilde{a}]$, where $\tilde{a}$ is a given level of abatement. The emissions generated from producing the quantity q_j by agent j equal ρq_j. The fixed costs involved in adoption of abatement technology are ignored, as these costs will not affect the firms' abatement and production decisions in the short run.[8]

The firms' costs of production are given by $c_j[q_j]$ and satisfy the classical assumption of having positive and non decreasing marginal costs, such that $c'_j[q_j] > 0, c''_j[q_j] \geq 0$. In addition, each firm may either have revenues or costs from trade in rights at price p. The demand for output is represented by the function $Q[t]$.

Social welfare, W, is the sum of the producers' surplus and consumers' surplus from trade in the polluting good, produced by the firms. Since it is assumed that the volume of rights traded in the economy is fixed, environmental quality is predetermined and the benefit from environmental quality can be considered as a constant effect on social welfare.

3. Trade Strategies

The dominant firm's strategy of price setting in the product market depends on the anticipated effect of a price increase in the product market on the behavior of the

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7 An example is the adoption of flue-gas desulfurization devices, commonly known as "scrubbers", to remove sulfur dioxide from the flue gases of coal-fired electric plant. Marginal abatement costs decreases with technology adoption of scrubbers technology, but increases with volume of abatement (Keohane 2003).

8 Including fixed costs into the system would better represent existing costs of pollution abatement. However, inclusion of fixed costs in the present analysis would not affect the conceptual characterization of the firms' behavior in the short run, which is the focus of the analysis. The model restricts attention to the behavior in a static short run period, which characterizes existing systems of trade in environmental rights. Leading examples include trade in fishing quota in New-Zealand (Newell et al. 2005), trade in water rights in south California (southern Colorado river), in which trade take place within a year circle, and trade in SO_2 allowances in the United States, within the Acid Rain Program. In the later, SO_2 allowances are yearly allocated and are mainly traded within the year. Trade through the auction system offers also a seven years advance auction. However, only a small share of the allocated allowances are traded within the auction system (U.S. Environmental Protection Agency 2005).

firms in the market for rights, and visa versa. Increasing the product price (relative to the perfectly competitive price) increases the output supplied by the fringe firms and decreases the output supplied by the dominant firm. These actions, in return, affect the relative volume of rights used by the firms. The fringe firms would increase their demand for rights, to control for the increase in pollution associated with the increase in production, and as a consequence, the price for rights would increase. The fringe firms may gain or lose from such an increase in the product price, depending on their role as buyers or sellers in the market for rights: In case the firms are buyers of rights, the increase in the product price would raise their costs in the market for rights and decrease their profits. In case the firms are sellers of rights, such a strategy would increase their revenues and on aggregate, increase their gain from trade. The dominant firm has an incentive to increase the product price even if such an increase results in an increase in its own costs in the market for rights, as long as the gain in the product market from such a strategic behavior overweighs the loss in the market for rights.

The fringe firms' objective is to maximize profits (Π_f), choosing the level of production, $S[t, p]$, and abatement, $a_f[t, p]$, or equivalently, the level of production and volume of pollution (rights to pollute), satisfying the regulatory pollution restrictions $a_f + x_f = \rho q_f$. Formally, the firms choose $S[t, p]$ and $a_f[t, p]$ such that

$$\{S[t, p], a_f[t, p]\} = \arg\max_{q_f, a_f} \quad \Pi_f = tq_f - p\left(x_f - (1-\alpha_d)R\right) - c_f[q_f] - g_f[a_f], \tag{1}$$

$$\text{s.t.} \quad a_f + x_f = \rho q_f.$$

The first term in the profit function represents the revenue from production, the second term represents the gain/loss from trade in rights, $c_f[q_f]$ represents the fringe firms' production costs and $g_f[a_f]$ represents the firms' abatement costs. Assuming $q_f > 0$ and $a_f > 0$, the firm's supply of output and abatement satisfy the first order conditions relating marginal costs to the observed prices:

$$t = c'[q_f] + \rho g'[a_f], \tag{2a}$$

$$p = g'[a_f]. \tag{2b}$$

Equation (2a) implies that optimality is achieved when the fringe firms' full marginal production costs are equalized with the product price, and equation (2b) implies that the volume of rights traded by the fringe firms is such that the firms' marginal cost of abatement is equalized with the price for rights. Equations (2a) and (2b) implicitly determine the optimal volume of rights demanded (used) by the fringe firms, $x_f[t, p]$, and the volume of rights traded by the fringe firms, $x_f^{Net} \equiv x_f[t, p] - (1-\alpha_d)R$.

The fringe firms' decisions about production and abatement are independent of the initial allocation of rights, and thus, the allocation of rights among competitive agents has no efficiency implications, as is well known (Coase 1960; Montgomery 1972; Hahn 1984). However, the decisions of the competitive firms are affected by the allocation of rights, through the impact of the allocation on the equilibrium

prices. Total differentiation of the fringe firms' necessary conditions (2a) and (2b) yields the following properties:

i. An increase in the price of rights results in a decrease in the volume of rights demanded by the fringe firms and their volume of production, i.e.,

$$\frac{dx_f[p,t]}{dp} < 0 \quad \text{and} \quad \frac{dS[p,t]}{dp} < 0;$$

ii. An increase in the product price increases the value of rights demanded by the fringe firms and their volume of production, i.e.,

$$\frac{dx_f[p,t]}{dt} > 0 \quad \text{and} \quad \frac{dS[p,t]}{dt} > 0.$$

The dominant firm simultaneously selects the prices that maximize its profits in the product market and in the market for rights, considering the aggregate costs from production $c_d[q_d]$ and abatement $g_d[a_d]$. Formally, the dominant firm chooses p^* and t^* such that

$$\{t^*, p^*\} = \arg\max_{t,p} \quad \Pi_d = tq_d - p(x_d - \alpha_d R) - c_d[q_d] - g_d[a_d], \tag{3}$$

s.t.

$$a_d + x_d = \rho q_d, \tag{3a}$$

$$q_d = Q[t] - S[t, p], \tag{3b}$$

$$x_d = R - x_f[t, p]. \tag{3c}$$

Equation (3a) is the regulatory constraint on pollution control; equation (3b) is the residual demand for output; and equation (3c) is the market-clearing condition for rights. The first order conditions for optimality imply that

$$(Q[t] - S[t, p]) + \left(t - c_d'[q_d] - \rho g_d'[a_d]\right)\left(Q'[t] - \frac{\partial S[t, p]}{\partial t}\right) = \left(g'[a_d] - p\right)\frac{\partial x_f[t, p]}{\partial t}, \tag{4}$$

$$\left(t - c_d'[q_d] - \rho g_d'[a_d]\right)\frac{\partial S[t, p]}{\partial p} = \left(p - g_d'[a_d]\right)\frac{\partial x_f[t, p]}{\partial p} - x_d^{Net}. \tag{4a}$$

where $x_d^{Net} = x_d[t, p] - a_d R$ is the net volume of rights traded by the dominant firm. Equation (4) implies that at the optimum the marginal profit in the product market from a change in t (LHS) is balanced with the marginal profitability in the rights market from a change in t (RHS). Equation (4a) implies that, at the optimum, the effect of a change in p on the marginal profitability in the output market (LHS) is balanced with the marginal profitability in the market for rights from a change in p (RHS). As the solution to the first order conditions depends on x_d^{Net}, the behavior of the dominant firm directly depends on the volume of rights it receives at the initial distribution.

In what follows, we turn our attention to the impact of the initial allocation of rights on the dominant firm's decisions. Total differentiation of the dominant firm's necessary conditions for optimality (equations (4) and (4a)) yields the following properties:

$$\frac{dp}{d\alpha_d} = \frac{-R}{|H_d|}\frac{\partial^2 \Pi_d}{\partial t \partial t} > 0, \qquad \text{and} \qquad \frac{dt}{d\alpha_d} = \frac{R}{|H_d|}\frac{\partial^2 \Pi_d}{\partial t \partial p} \gtreqless 0, \tag{5}$$

where H_d is the Hessian matrix of the dominant firm's profit function. An increase in the share of rights allocated to the dominant firm increases the price of rights, as a result of an increase in the residual demand for rights.[9] Following Salop and Scheffman (1987), a sufficient condition for the dominant firm to profit from such a raise in the price for rights is that the vertical shift in the dominant firm's residual demand curve (or equivalently, the change in output price, t) must exceed the increase in its average costs, given by

$$AC = \frac{c_d[q_d] + g_d[a_d] + p x_d^{\text{Net}}}{q_d}. \tag{6}$$

From the first order conditions (4) and (4b) it follows that the shift in the dominant firm's residual demand curve for output, as a result of a change in p is as follows:

$$\frac{dt}{dp} = \frac{(p - g_d'[a_d])\partial x_f/\partial p - x_d^{\text{Net}}}{(p - g_d'[a_d])\partial x_f/\partial t + q_d}. \tag{7}$$

Equations (6) and (7) imply that the firm is more likely to benefit from an increase in p the smaller the net demand for rights by the dominant firm (x_d^{Net} small), or equivalently, (i) the larger the share of rights allocated to the dominant firm; and (ii) the smaller the volume of rights allocated in the system. This implies that an increase in the share of rights allocated to the dominant firm is likely to increase adoption of a raising-rivals'-cost strategy.

The effect of a change in the allocation of rights on the output price is ambiguous. This is because on the one hand, an increase in α_d increases the fringe firms' costs and, as a consequence, decreases their production and increases the residual demand for output facing the dominant firm. On the other hand, an increase in α_d increases the volume of rights used by the dominant firm, and thus decreases its marginal costs. As a result, the aggregate effect of an increase in the share of rights on the equilibrium price for the product depends on the relative effect of the reallocation of rights on the costs of the firms. The ambiguity in the effect of a change in the allocation vector on the product price determined by the dominant firm is graphically presented in Figure 1.

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9 Since the second order conditions require $\partial^2 \Pi_d/\partial t \partial t < 0$ and $|H_d| > 0$, the sign of $dp/d\alpha_d$ is positive.

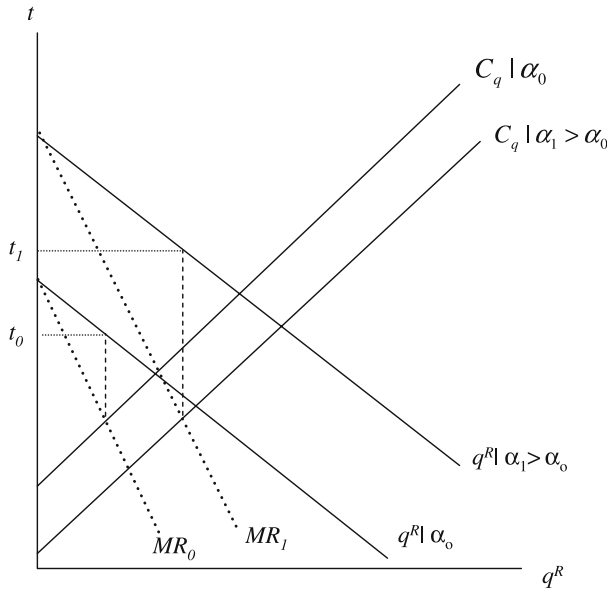

Figure 1. The effect of a change in α_d on the product price, t.

In Figure 1, we present the residual demand for the product by the line $q^R = Q[t] - S[t, p]$ and the marginal production costs for the dominant firm by the line $C_q = c'[q_d] + \rho g'_d[a_d]$. The equilibrium price in the product market depends on the relative shift out of the residual demand curve and the marginal cost curve, and thus a change in the allocation parameter α_d may result in an increase or a decrease in the product price set by the dominant firm.[10]

To conclude, the dominant firm increases the price for rights with an increase in its share of rights α_d, but at the same time, it may increase or decrease the product price, as a result of the change in α_d. The efficiency implications of such changes are analyzed in the section that follows.

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10 Formally, the change in the output price depends on the sign of $\partial^2 \Pi_d / \partial t \partial p$. From equation (4) it follows that

$$\frac{\partial^2 \Pi_d}{\partial t \partial p} = \frac{\partial}{\partial p}\left[q_d[t, p] + (t - c'_d[q_d] - \rho g'_d[a_d])\frac{\partial q_d[t, p]}{\partial t}\right] - \frac{\partial}{\partial p}\left[\left(g'_d[a_d] - p\right)\frac{\partial x_f[t, p]}{\partial t}\right],$$

which cannot be signed in the most general case.

4. Efficiency in Abatement and Production

The initial allocation of rights affects the strategies of the agents and therefore, has a direct effect on the efficiency of the markets in production and abatement.[11] The marginal inefficiency in the market for rights is equal to the gap, at equilibrium, between the marginal abatement costs of the fringe firms and those of the dominant firm. Considering the optimality conditions (2b) and (4a), the difference between these costs, at equilibrium, equals

$$p - g'_d[a_d] = \frac{x_d^{\text{Net}}}{\partial x_f[t, p]/\partial p} + \frac{\left(t - c'_d[q_d] - \rho g'_d[a_d]\right)\partial S[t, p]/\partial p}{\partial x_f[t, p]/\partial p}. \tag{8}$$

That is, the inefficiency in abatement results from a price markup or markdown in the market for rights, and it depends on the net volume of rights traded by the dominant firm (first term on the RHS), and on the dominant firm's marginal profitability in the product market (second term on the RHS). Equation (8) implies that when the dominant firm is a seller of rights, i.e., $x_d^{\text{Net}} < 0$, the dominant firm sets p higher than its marginal abatement costs, $p > g'_d[a_d]$, raising the rivals' costs.[12] However, the dominant firm may set p higher than its marginal abatement costs even if the firm is a buyer of rights, which implies an increase in the firm's own costs. Equation (8) implies that the firm will do so only if it has market power in the product market (when $t - c'_d[q_d] - g'_d[a_d] > 0$). A dominant firm who is a buyer of rights will increase the price for rights above its marginal abatement costs if the decrease in profitability in the market for rights (from setting $p > g'_d[a_d]$) is overweighed by the increase in profitability in the product market: An increase in p decreases the volume of output produced by the fringe firms, and thus increases the residual demand for the product and increases the dominant firm's marginal profitability (price markup) in the product market. In that case, by raising the cost of rights (to itself), and also by buying more rights, the dominant firm strengthens its position in the product market. Clearly, when the dominant firm is not able to set a price markup in the product market (when $t - c'_d[q_d] - \rho g'_d[a_d] = 0$), a dominant firm that buys rights would always set the price for rights below its marginal abatement costs, $p < g'_d[a_d]$.

A reallocation of rights by the regulator would determine the role of the dominant agent in the system and directly affect the efficiency in abatement. The effect of a redistribution of rights on the efficiency in abatement depends on whether at equilibrium $p > g'_d[a_d]$ or $p < g'_d[a_d]$. When $p > g'_d[a_d]$, a reallocation of rights from the competitive agents to the dominant firm clearly decreases the efficiency of the market for rights if $dt/d\alpha_d > 0$, because then, an increase in α_d increases p and as a

11 The allocation has no effect on the environmental quality as it is assumed that the firms use all the rights they hold after the trade and that non-polluting agents do not trade in rights.

12 Differentiation of the fringe firms' necessary conditions (2a) and (2b) yields the following properties: $\partial x_f[t, p]/\partial p < 0$ and $\partial S[t, p]/\partial p < 0$.

result, the volume of pollution abated by the fringe firms increases and the volume of pollution abated by the dominant firm decreases:

$$\frac{da_f}{d\alpha_d} = \frac{\partial a_f}{\partial p}\frac{dp}{d\alpha_d} = \frac{1}{g''_f[\cdot]}\frac{dp}{d\alpha_d} > 0,$$
$$\frac{da_d}{d\alpha_d} = -\frac{1}{g''_f[\cdot]}\frac{dp}{d\alpha_d} + \rho Q'[t]\frac{dt}{d\alpha_d} < 0.$$

The fringe firms increase abatement as the alternative cost of controlling pollution increases (p increases). The dominant firm increases the volume of rights it holds and decreases abatement, for increasing its profitability.[13] Consequently, the gap between the marginal abatement costs of the firms increases, and efficiency in abatement decreases. In the same way, when $p < g'_d[a_d]$, a reallocation of rights from the fringe firms to the dominant firm increases efficiency in abatement, as such a reallocation of rights would decrease the gap between the firms' marginal abatement costs.

The efficiency in the production depends on the relative efficiency in the market for rights and on the elasticity of the residual demand for the product. From equation (4) it follows that the aggregate effect of these factors on the efficiency in the product market is given by

$$t - c'_d[q_d] - \rho g'_d[a_d] = \frac{\left(g'_d[a_d] - p\right)\partial x_f/\partial t}{Q'[t] - \partial S[t, p]/\partial t} - \frac{Q[t] - S[t, p]}{Q'[t] - \partial S[t, p]/\partial t}, \tag{9}$$

As $\partial x_f/\partial t$ and $\partial S[t, p]/\partial t$ are positive, equation (9) implies that efficiency in production decreases when the dominant firm sets a price for rights greater than its marginal abatement cost. This is because the higher the price market up in the market for rights, the greater the gap between the residual demand for the product and the marginal costs of production of the dominant firm. As a result, a higher markup in the market for rights implies a higher markup in the product market.

The direct consequence of the above relationship between the efficiency in the market for rights and the efficiency in the product market is that an increase in the initial share of rights allocated to the dominant firm would increase the dominant firm's market power in the market for rights and in the product market, and as a consequence, it would decrease efficiency in the product market. The above relation also implies that in a system in which the dominant firm takes the role of a seller in the market for rights would result in lower production efficiency than a system in which the dominant firm takes the role of a buyer in the market for rights. Summarizing the analysis up to this point yields the following proposition:

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13 However, when an increase in the share of rights α_d decreases the product price t, an increase in the share of rights to the dominant firm may result in an increase in the volume of pollution abated by the dominant firm. In such a case, it is not clear whether an increase in α_d increases or decreases the efficiency of the rights market, as the gap between the firms' marginal costs may either increase or decrease.

Proposition 1. *When the dominant firm is a seller of rights and* $dt/d\alpha_d > 0$*, a decrease in the share of rights allocated to the dominant firm would increase efficiency in both abatement and production, as such a reallocation of rights will decrease the gap between the price set by the dominant firm and the firm's marginal costs in the market for rights and in the product market. Consequently, any allocation of rights that leads the dominant firm to be a seller of rights is dominated by at least one allocation in which the dominant firm is a buyer of rights.*

5. Optimal Criterion for the Allocation of Rights

Let the optimal criterion for the allocation of rights be the one that maximizes social welfare. Considering a system in which all related markets are imperfectly competitive, the regulator's problem is to determine an optimal allocation $\boldsymbol{\alpha}^* = \{\alpha_d^*, 1-\alpha_d^*\}$ such that

$$\alpha_d^* = \arg\max_{\alpha_d} \quad W[\alpha_d] \stackrel{\text{def}}{=} \Pi_f[q_f^*, x_f^*; \alpha_d] + \Pi_d[t^*, p^*; \alpha_d] + \int_{t^*}^{\infty} Q[t]dt,$$

where $\Pi_f[\cdot]$ and $\Pi_d[\cdot]$ are the maximized profit functions of the fringe firms and the dominant firm, respectively, and $\int_{t^*}^{\infty} Q[t]dt$ is the consumer' surplus from trade in the output.

The discussion in section 3 suggests that the dominant firm would benefit from an increase in its share of rights. The aggregate effect of a change in the share of rights allocated to the dominant firm on the firm's profits is positive, and is given by

$$\frac{d\Pi_d[p^*, t^*; \alpha_d]}{d\alpha_d} = p^* R > 0. \tag{10}$$

However, the fringe firms may or may not benefit from an increase in the share of rights allocated to the dominant firm, since there are two separate effects on the fringe firms' profits. First, an increase in the share of rights allocated to the dominant firm increases the net demand for rights by the fringe firms, and as a consequence, the price for rights increases. This, in turn, affects the fringe firms' costs of trade in rights and abatement. Second, because the dominant firm chooses a new output price, the profits of the fringe firms are further affected. The impact of the allocation of rights on the production and demand for rights depends on the relative effect of the allocation on the prices p and t. The aggregate effect of a change in the share of rights on the fringe firms' profits is found by differentiating their maximized profit function with respect to the allocation parameter α_d:

$$\frac{d\Pi_f[q_f^*, x_f^*; \alpha_d]}{d\alpha_d} = S[t^*, p^*]\frac{dt^*}{d\alpha_d} - \left[\left(x_f^* - (1-\alpha_d)R\right)\frac{dp^*}{d\alpha_d}\right] - p^* R. \tag{11}$$

The allocation of rights that maximizes social welfare, subject to the presence of strategic behavior in the markets, satisfies the following necessary first order

condition for optimality:

$$\frac{d\Pi_d[p^*, t^*; \alpha_d]}{d\alpha_d} + \frac{d\Pi_f\left[q_f^*, x_f^*; \alpha_d\right]}{d\alpha_d} - Q[t^*]\frac{dt^*}{d\alpha_d} = 0. \tag{12}$$

Substituting equations (10) and (11) into (12) we find that the optimal allocation of rights is such that

$$-(Q[t^*] - S[t^*, p^*])\frac{dt^*}{d\alpha_d} - (x_f[p^*, t^*] - (1-\alpha_d)R)\frac{dp^*}{d\alpha_d} = 0, \tag{13}$$

or, equivalently, that at the optimum

$$q_d^*\frac{dt^*}{d\alpha_d} = x_d^{Net}\frac{dp^*}{d\alpha_d}, \tag{14}$$

where $q_d^* = Q[t^*] - S[t^*, p^*]$ is the dominant firm's volume of production and $x_d^{\text{Net}} \equiv x_d^* - \alpha_d R$ is the volume of rights traded by the dominant firm. By construction, the optimality condition (14) implies that social welfare is maximized when the marginal social benefit from allocating rights to the dominant firm equals zero, and it implies the following characteristics:

Proposition 2. *Social welfare is maximized when the marginal inefficiency in the market for rights, weighted by the effect of the allocation on the volume of rights used by the dominant firm, is balanced with the marginal inefficiency in the product market, weighted by the effect of the allocation on the dominant firm's production. That is, the optimal allocation of rights,* $\bar{\boldsymbol{\alpha}} \in \boldsymbol{\alpha}$*, satisfies the equality*

$$(t^* - c'[q_d^*] - \rho g_d'[a_d^*])\frac{dq_d^*}{d\alpha_d} = (p^* - g_d'[a_d^*])\frac{dx_d^*}{d\alpha_d}.$$

Proof. See Appendix A. ■

That is, the environmental rights can be used as a tool to balance inefficiencies in abatement and production, that result from strategic behavior of the firms, and by adopting the optimal rule of allocation, efficiency of the regulatory mechanism can increase.

Proposition 3. *At the optimum, if the dominant firm is a buyer of rights,* $(x_d - \alpha_d R) > 0$*, the product price increase with an increase in the allocation of rights to the dominant firm: i.e.,* $(x_d - \alpha_d R) > 0 \Rightarrow dt/d\alpha_d > 0$*; and if the dominant firm is a seller of rights,* $(x_d - \alpha_d R) < 0$*, the product price decreases with an increase in the share of rights initially allocated to the dominant firm: i.e.,* $(x_d - \alpha_d R) < 0 \Rightarrow dt/d\alpha_d < 0$.

Proposition 3 follows directly from equation (14) and it suggests that for optimality, the regulator should allocate a relatively small share of the rights to the dominant firm, such that it would enhance monopsony power, if an increase in α_d

increases the product price, and that the regulator should allocate a relatively big share of the rights to the dominant firm, such that it would enhance monopoly power, if an increase in α_d decreases the product price.

Having developed the imperfectly competitive benchmark, the discussion now turns to alternative cases where one or both markets are competitive. Consider first the case of a perfectly competitive system in which no firm has market power in either markets. In such a framework, it is easily seen that since $dp/da_d = dt/da_d = 0$, and the allocation criterion (14) has no efficiency implications. Further, suppose that the system includes an imperfectly competitive market for rights and a competitive product market. In such a case, the allocation criterion in (14) implies that optimality is achieved only when $x_d^{\text{Net}} dp^*/d\alpha_d = 0$. This equality is satisfied only when the dominant firm is allocated precisely the quantity of rights that it would have demanded to maximize its profits, i.e., when $x_d^{\text{Net}} = 0$, a result consistent with previous analysis conducted by Hahn (1984). The rationale underlining this solution is that such an allocation eliminates power from the market for rights, such that no pecuniary externalities are present. In that case, the optimal allocation can achieve a first-best outcome. At last, we consider a system that includes a competitive market for rights and an imperfectly competitive output market. In such a system, as in the perfectly competitive system, the allocation of rights would not affect the price in the markets, $dt^*/da_d = dp^*/da_d = 0$, and thus, the initial distribution of rights has no welfare implications.

6. An Illustrative Example

This section illustrates, through a simple example, the implications of adopting the proposed criterion of allocation on the prices set by a dominant firm and on social welfare. One particular observation is that when a given allocation of rights increases the price for rights and as a consequence also the product price, reallocating rights so as to cause the dominant firm to become a buyer in the market for rights could be welfare improving.[14] The rationale for such a result is that a decrease in the share of rights to the dominant firm increases the efficiency in the market for rights when the dominant firm is a seller of rights, and may also increase efficiency in the product market. This is because the lower the allocation of rights to the dominant firm, the lower the price for rights, the lower the costs of the fringe firms, and, thus, the higher their output and the lower the residual demand for output observed by the dominant firm. In such a case, it is clearly welfare improving to decrease the share of rights initially allocated to the dominant firm such that it is no longer a seller of rights. It would be efficient to further decrease the allocation of rights to the dominant firm, such that it would be

14 Misiloke and Elder (1989) show that in a system of imperfectly competitive markets, an increase in p is likely to have a passing-on effect, increasing marginal profitability in the product market and raising the price for the product.

a buyer of rights as long as the increase in efficiency in the product market outweighs the inefficiency in the market for rights, which results from the dominant firm exercising monopsony power in the purchase of rights.

For simplicity, we present an example in which the dominant firm and the fringe firms are assumed to have identical production costs, represented by the function $c[q_j]=\beta q_j^2$, $\beta>0$. As in the theoretical model, I attribute the source of dominance of the firm type d to its superior abatement technology. Specifically, let $g_f[a_f]=1/2a_f^2$ be the abatement cost function of the fringe firms, and $g_d[a_d]=\kappa/2a_d^2$ be the abatement cost function of the dominant firm. The parameter $\kappa\in[0,1]$ represents the relative efficiency of the firm's abatement technology, and a_j is the firm type j's level of abatement, which is by construction $a_j=\rho q_j-x_j$.

The equilibria in the markets and the welfare distribution are determined by the three parameters that characterize the firms: ρ,β and κ, and by the volume of rights allocated, R. To conduct the simulation, it is necessary to assign specific values for the parameters. The following starting values were chosen: $\rho=0.8$; $\beta=0.5$; and $\kappa=0.9$, and the aggregate volume of rights was set at $R=2$. The dominant firm observes a residual demand for the product that equals $Q[t]-S[t,p]$. The demand for the product, $Q[t]$, is given by the function $Q[t]=7-t$.

The fringe firms observe the market prices and select the optimal level of production and volume of rights, to maximize profits. The interior solutions to the fringe firms' problem is

$$S[t,p]=t-0.8p \quad \text{and} \quad x_f[t,p]=0.8t-1.64p.$$

The dominant firm chooses the prices in the market for rights and in the output market to maximize profits. Solving the dominant firm's problem as specified in equation (3), we find that the dominant firm sets prices as follows:

$$p^*=0.6+0.487\alpha_d,$$
$$t^*=2.924+0.14\alpha_d.$$

In this example both prices increase with an increase in the share of rights allocated to the dominant firm, as illustrated in Figures 2 and 3.[15] Figure 2 presents the equilibrium price for the product, given different values of α_d, and Figure 3 presents the equilibrium price for rights for different values of α_d. For a benchmark comparison, I also present the prices that would have evolved in a system in which the product market is perfectly competitive and where the market for rights is imperfectly competitive (referred as a C–IC system of markets), given different values of α_d.[16] The figures illustrate the increase in prices set by the dominant firm

15 The selected functions imply $\partial^2\Pi_d/\partial t\partial p>0 \quad \forall\alpha_d$, and thus output price increases with α_d, for all α_d.

16 When considering the C-IC system, the product price was determined by the market-clearing condition $q_d+q_f=Q[t]$. The optimal price for rights set by the dominant firm is $p=0.48+0.42\alpha_d$ and the corresponding output price is $t=2.693+0.0094\alpha_d$.

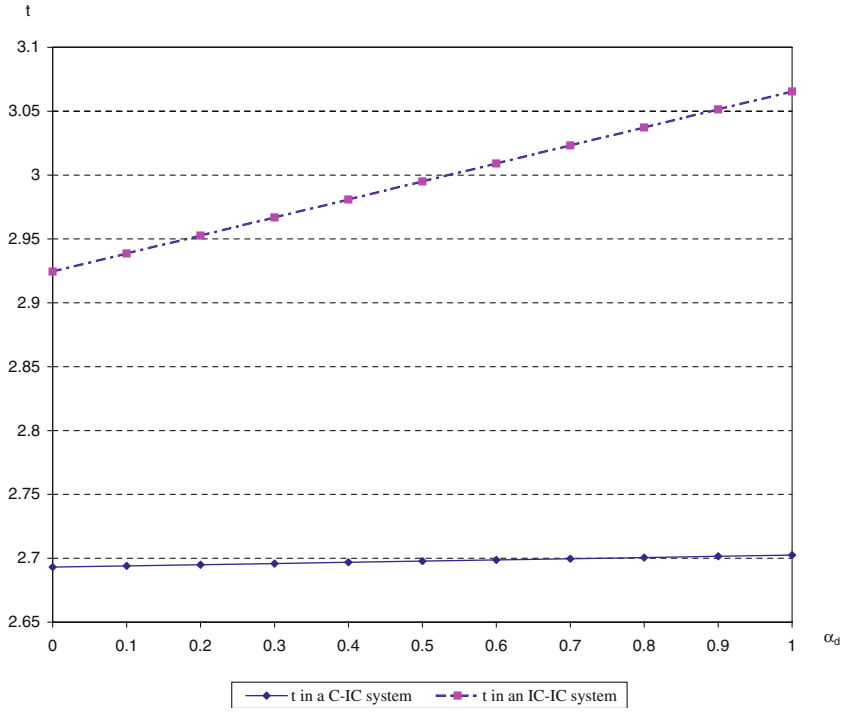

Figure 2. Product price as a function of the dominant rm's share of rights.

when all markets are imperfectly competitive (referred as an IC–IC system) relative to the prices set in a C–IC system of markets. As a result of market power in the product market, the dominant firm increases not only the product price but also the price for rights as a function of α_d.

The prices determined by the dominant firm depend on the initial allocation of rights, and it is transparent that the dominant firm is more likely to adopt a raising-rivals-costs strategy when its share in the initial allocation increases: In case $\alpha_d = 0$, the difference between the price for rights set in the IC–IC system and the price for rights set in the C–IC system equals 0.120, while when $\alpha_d = 1$, the difference in the price for rights that is set in an IC–IC system and that price in a C–IC system equals 0.187. A similar pattern occurs takes place in the product market.

The fringe firms' supply of output and demand for rights increase with output price and decrease with rights price. For the selected initial values for the parameters, we find that, an increase in the initial allocation of rights to the dominant firm always decreases the fringe firms' profits. Consumers' surplus from the consumption of Q always decreases with an increase in α_d, as a result of an increase in the price t. However, social welfare may increase with an increase in the share of rights allocated to the dominant firm, as a result of an increase in the profits of

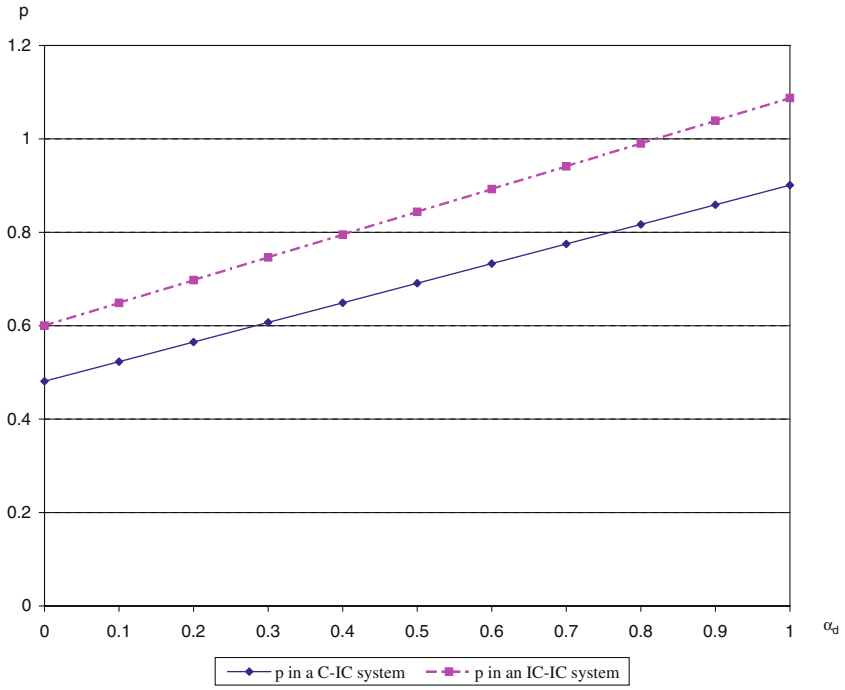

Figure 3. Price for rights as a function of the dominant rm's share of rights.

the dominant firm. Figure 4 illustrates the effect of the initial allocation of rights on social welfare.

Social welfare reaches its maximum when, in this example, the dominant firm receives 12.8% of the rights. Given this allocation, the dominant firm is a buyer of rights and the fringe firms are sellers of rights in equilibrium ($\alpha_d R = 0.256$ and $x_d = 0.732$). In this example, when the initial allocation of rights is such that the dominant firm receives 49% of the rights, the dominant firm does not trade in rights. Clearly, while such an allocation is socially optimal for the C-IC structure of markets, it is in general not socially optimal in an IC–IC structure of markets.

7. Summary and Policy Implications

Before adopting market-based regulation in markets characterized by imperfect competition, the effect of the initial allocation of tradable rights on the strategies of the agents should be carefully weighed, as the allocation has efficiency consequences in production and abatement. In contrast to the case of perfectly competitive product markets, when the product market is imperfectly competitive the regulator can use the distribution of rights to firms with market power as a tool with which to balance inefficiencies in abatement and production that result from

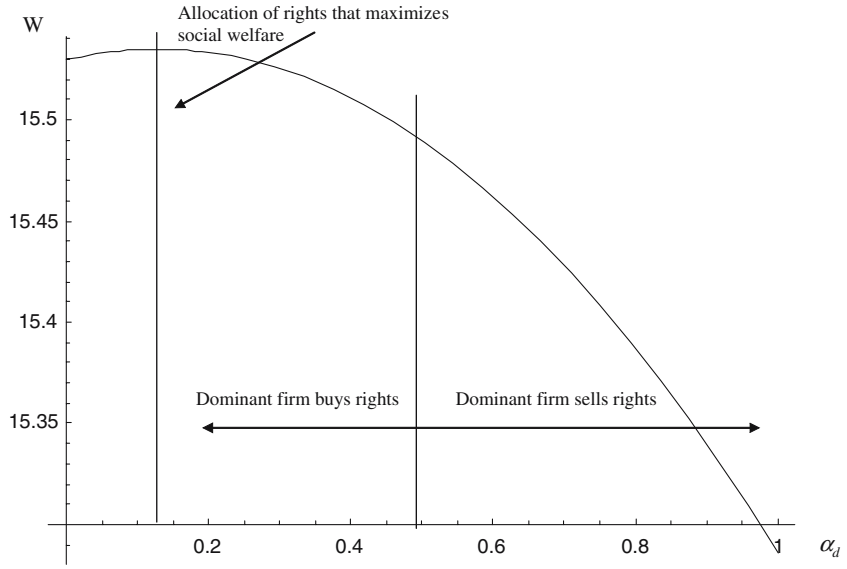

Figure 4. Rights allocation and social welfare in a system in which market power is present in the market for rights and in the product market.

the imperfectly competitive behavior of these firms. By allowing the firm with market power to operate in the market for rights as a buyer or seller, we can increase the efficiency of the two markets relative to the case in which the firm dominates the output market and is not allowed to trade in rights or in which the market is regulated through emissions quotas.

The analysis suggests that in order to maximize social welfare, the allocation of rights among agents should balance the marginal inefficiency in the market for rights, weighted by the effect of the allocation on the volume of rights traded, with the marginal inefficiency in the product market, weighted by the effect of the allocation on the volume of output traded. The optimal allocation implies a market design in which if an increase in α_d increases the product price, the dominant firm should be allocated a relatively small share of the rights, such that it would enhance monopsony power in the market for rights, and if an increase in its share of rights decreases the product price, the dominant firm should be allocated a relatively big share of the rights, such that it would enhance monopoly power in the market for rights.

Since the allocation of rights among competitive agents has no efficiency implications, the regulator need not take it into account for the purposes of economic efficiency. Implementation of the optimal criterion for allocation of rights does not require any direct information about the costs of the firms, an attribute that may facilitate implementation of such an allocation rule. However, the proposed rule requires information about the volume of rights traded by regulated firms and the relative power of the firms in the product market and in the market for rights.

Such information may be available in systems that already involve trade in rights, but may be hard to estimate when establishing new markets. The derived optimality criterion is nevertheless valuable in assessing the efficiency of existing regulated market-based systems. Provided that information is available about the volume of trade by competitive and non-competitive agents and about the revealed prices, the regulator can identify and improve the relative inefficiency in the system, through a reallocation of rights among competitive and non-competitive polluting firms.

Appendix A Proof of Proposition 2

The optimality conditions (2b) and (4) imply that

$$q_d^* = (g_d'[a_d] - g_f'[a_f])\frac{\partial x_f}{\partial t} - (t - c_d'[q_d] - \rho g_d'[a_d])(Q'[t] - \frac{\partial S[t,p]}{\partial t}) \tag{A.1}$$

and the optimality conditions (2b) and (4) imply that

$$x_d^{Net} = -(t - c_d'[q_d] - \rho g_d'[a_d])\frac{\partial S[t,p]}{\partial p} - (g_d'[a_d] - g_f'[a_f])\frac{\partial x_f[t,p]}{\partial p}. \tag{A.2}$$

Substituting Equations (A.1) and (A.2) into Equation (14) we find that, optimality in allocation implies,

$$\begin{aligned}&\left((g_d'[a_d] - g_f'[a_f])\frac{\partial x_f}{\partial t} - (t - c_d'[q_d] - \rho g_d'[a_d])(Q'[t] - \frac{\partial S[t,p]}{\partial t})\right)\frac{dt^*}{d\alpha_d}\\ &= \left(-(t - c_d'[q_d] - \rho g_d'[a_d])\frac{\partial S[t,p]}{\partial p} - (g_d'[a_d] - g_f'[a_f])\frac{\partial x_f[t,p]}{\partial p}\right)\frac{dp^*}{d\alpha_d}.\end{aligned} \tag{A.3}$$

Equivalently, after collecting terms, we get

$$\begin{aligned}&-\left(t - c_d'[q_d] - \rho g_d'[a_d]\right)\left((Q'[t] - \frac{\partial S[t,p]}{\partial t})\frac{dt}{d\alpha_d} - \frac{\partial S[t,p]}{\partial p}\frac{dp}{d\alpha_d}\right)\\ &= (g_d'[a_d] - g_f'[a_f])\left(-\frac{\partial x_f}{\partial t}\frac{dt}{d\alpha_d} - \frac{\partial x_f}{\partial p}\frac{dp}{d\alpha_d}\right),\end{aligned} \tag{A.4}$$

where t and p are at their optimum, t^* and p^*, respectively. As $q_d[t,p] = Q[t] - S[t,p]$, the term in the second brackets on the LHS is the derivative of $q_d[t,p]$ with respect to α_d, i.e,

$$\left((Q'[t] - \frac{\partial S[t,p]}{\partial t})\frac{dt}{d\alpha_d} - \frac{\partial S[t,p]}{\partial p}\frac{dp}{d\alpha_d}\right) = \frac{dq_d[t,p]}{d\alpha_d},$$

and as $x_d = R - x_f[t,p]$, the term in the second brackets on the RHS is the derivative of $x_d[t,p]$ with respect to α_d. i.e,

$$\left(-\frac{\partial x_f}{\partial t}\frac{dt}{d\alpha_d} - \frac{\partial x_f}{\partial p}\frac{dp}{d\alpha_d}\right) = \frac{dx_d[t,p]}{d\alpha_d}.$$

As a result, at equilibrium,

$$(t - c_d'[q_d] - \rho g_d'[a_d])\frac{dq_d[t, p]}{d\alpha_d} = (g_f'[a_f] - g_d'[a_d])\frac{dx_d[t, p]}{d\alpha_d}. \quad \text{(A.5)}$$

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