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Multi-Sector Model of Tradable Emission Permits

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Abstract

This paper presents a multi-sector model of tradable emission permits, which includes oligopolistic and perfectly competitive industries. The firms in oligopolistic industries are assumed to exercise market power in the tradable permit market as well as in the product market. Specifically, we examine the effects of the initial permit allocation on the equilibrium outcomes, focusing on the interaction among these product and permit markets. It is shown that raising the number of initial permits allocated to one firm in an oligopolistic industry increases the output produced by that firm. Under certain conditions, raising a "clean" (less-polluting) firm's share of the initial permits can lead to reductions in both the product and permit prices. We discuss criteria for the socially optimal allocation of initial permits, considering the trade-off between production inefficiency and consumer benefit.

Key words: tradable emission permits, initial allocation, multi-sector model, Cournot oligopoly, market power

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1 Introduction

Market-based environmental regulation in the form of tradable emission permits has attracted increasing attention over the past decades. Under the idealized conditions of perfect competition, a tradable permit system yields the optimal allocation of resources. However, in the presence of market power in either the permit market or the related product market, a tradable permit system would not achieve efficient outcomes.

Assuming perfectly competitive product and permit markets, Montgomery (1972) shows that tradable permits reduce pollution to given standards of environmental quality at the least cost to the related industry. He also formally proves that the initial allocation of permits does not affect the equilibrium outcomes as long as the permit market is perfectly competitive.

However, many product markets are imperfectly competitive. For example, the electric power industry, which emits significant amounts of greenhouse gases, tends to be oligopolistic. Moreover, permit markets can also be imperfectly competitive. Even though market power in permit markets might be of less concern when the markets are composed of many small firms, it could be a serious problem in more localized permit markets.

One notable example of localized permit markets is California's Regional Clean Air Incentives Market (RECLAIM), established by the South Coast Air Quality Management District. The RECLAIM program adopted a cap and trade system for NOx and SO2 in order to help meet the state and federal ambient air quality standards in the Los Angeles Basin, which suffers some of the worst air pollution in the U.S. Kolstad and Wolak (2008) empirically examine the interaction of RECLAIM (permit market) with the California electricity market (product market).[1] They suggest that the oligopolistic electric utilities that participated in the California electricity market raised the NOx permit price particularly during 2000 and 2001, exerting market power in RECLAIM.

Hahn (1984) is the first to theoretically study the market power problem in a tradable permit system, by using a dominant firm-competitive fringe model.[2] His model assumes market power in the permit market, while all the firms are assumed to be price takers in the product market. He demon-

[1] See also Fowlie et al. (2009) for a detaild discussion of RECLAIM, including a comparison of the effects of a cap and trade system and a command and control approach.

[2] See, for example, Tietenberg (2006) and Montero (2009) for a detailed discussion of the market power problem in a tradable permit system.

strates how a single dominant firm can manipulate the permit price to its own advantage, which reduces the cost-effectiveness of a tradable permit system. Specifically, he shows that the initial allocation of permits affects the equilibrium outcomes in the presence of market power. Westskog (1996) extends Hahn's dominant firm-competitive fringe model into a Cournot model in the permit market.

The assumption of Hahn (1984) that all firms are price takers in the product market does not hold true for many industries. Misiolek and Elder (1989) extend Hahn's market structure to the product market, and investigate the interaction with the permit market. They show that a single dominant firm manipulates the permit market in an effort to drive up the fringe firm's cost in the product market.[3] Eshel (2005) discusses the optimal allocation of tradable emission permits within a dominant firm-competitive fringe model as in Misiolek and Elder. von der Fehr (1993) and Sartzetakis (1997) extend the model of Misiolek and Elder to incorporate Cournot competition.[4]

Most previous work has assumed a single industry (product market) for the analysis of the market power problem. One of the exceptions is Nagurney and Dhanda (1996), who consider two different industries with different competition structures, namely, an oligopoly and a perfect competition. However, they assume that all the firms in both industries are price takers in the permit market. Thus, in their model, the initial allocation of permits does not affect the equilibrium pattern.

In the present paper, we consider two different industries with different competition structures—a Cournot oligopoly and a perfect competition, in line with Nagurney and Dhanda (1996). However, in contrast to Nagurney and Dhanda, it is assumed that the firms in the oligopolistic industry can exercise market power in the tradable permit market as well as in the product market, while those in the perfectly competitive industry are price takers in the permit market. Specifically, we examine the effects of the initial permit allocation on the equilibrium outcomes, focusing on the interaction among these product and permit markets. It is shown that raising the number of initial permits allocated to one firm in the oligopolistic industry increases the output produced by that firm since the initial distribution of permits

[3]See also Salop and Scheffman (1983).

[4]More recently, Chen and Hobbs (2005) and Chen et al. (2006) consider oligopolistic models, and examine the interaction between the Pennsylvania–New Jersey–Maryland Interconnection (PJM) electricity market and the Ozone Transport Commission (OTC) NOx Budget program in the northeastern U.S.

functions as a subsidy. Under certain conditions, raising the "clean" (less-polluting) firm's share of the initial permits can lead to reductions in both the product and permit prices. Moreover, we show criteria for the socially optimal allocation of initial permits, considering the trade-off between production inefficiency and consumer benefit.

The paper is organized as follows: Section 2 presents a multi-sector model of tradable emission permits, which includes oligopolistic and perfectly competitive industries. Section 3 analyzes the effects of the initial permit allocation on the equilibrium outcomes in detail. Section 4 illustrates the theoretical results with a stylized numerical example. Section 5 contains the concluding remarks.

2 The Model

2.1 Overview

We consider two industries (and hence two different products) with different competition structures. It is assumed that one industry is a Cournot oligopoly, while the other industry, consisting of a large number of firms, is perfectly competitive.

All the firms in both industries emit pollution as a by-product, and the pollutant is common among them. The firms in both industries are subject to environmental regulation based on a tradable permit system, in which the initial permits are allocated for free (i.e., grandfathering). We assume that the firms in the oligopolistic industry can exercise market power in the tradable permit market as well as in the product market. In contrast, we assume that the firms in the perfectly competitive industry are price takers in the permit market as well as in the product market.

Throughout the paper, all functions are assumed to be twice continuously differentiable.

2.2 Perfectly Competitive Industry

In the perfectly competitive industry, firm i has a cost $\widehat{C}_i(\widehat{q}_i)$ of producing the quantity $\widehat{q}_i$. We assume that $\widehat{C}_i' > 0$ and $\widehat{C}_i'' > 0$. The firms in this industry take the product price $\widehat{P}$ as given since they are assumed to be price takers. $\widehat{P}\widehat{q}_i - \widehat{C}_i(\widehat{q}_i)$ represents firm i's profit in the product market.

We here focus on the short-run model in which emission abatement technologies, and hence emission rates of the pollutant, are fixed during a given period of time. Emissions of each firm are proportional to its output, i.e., $\widehat{r}\widehat{q}_i$, where $\widehat{r} > 0$ denotes each firm's emission rate of the pollutant. For simplicity, we assume that the emission rate is the same among firms in this industry.

Each firm is initially issued tradable emission permits $\widehat{e}_i > 0$. Then, the firms can trade these permits in the permit market. $\widehat{r}\widehat{q}_i - \widehat{e}_i$ represents the number of tradable emission permits purchased (positive) or sold (negative) by firm i. Multiplied by the permit price P^e, $P^e\left(\widehat{r}\widehat{q}_i - \widehat{e}_i\right)$ represents the net expense of tradable permits. Note that firms take the permit price P^e as given since they are assumed to be price takers in the permit market.

Firm i in the perfectly competitive industry solves the following profit maximization problem:

$$\max_{\widehat{q}_i} \; \widehat{P}\widehat{q}_i - \widehat{C}_i(\widehat{q}_i) - P^e\left(\widehat{r}\widehat{q}_i - \widehat{e}_i\right) \tag{1}$$

s.t.

$$\widehat{q}_i \geq 0. \tag{2}$$

Assuming an interior solution, we obtain the following first order condition for firm i's problem:

$$\widehat{P} = \widehat{C}_i'(\widehat{q}_i) + \widehat{r}P^e. \tag{3}$$

It should be emphasized that a tradable permit system is essentially equivalent to a "tax and subsidy" system. When firms are price takers in the permit market, the tradable permit system imposes a "specific tax" $P^e\widehat{r}\widehat{q}_i$, while providing a "lump-sum subsidy" $P^e\widehat{e}_i$ to each firm. Indeed, equation (3) implies that each firm faces a "tax" $\widehat{r}P^e$ per unit of product, or P^e per unit of pollution. In other words, $\widehat{r}P^e$ or P^e can be interpreted as a "marginal tax." Thus, if P^e rises, each firm decreases its quantity of product, $\widehat{q}_i$, and hence its emissions, $\widehat{r}\widehat{q}_i$. In contrast, the "lump-sum subsidy" $P^e\widehat{e}_i$ does not affect the decision of the firm. Therefore, as is well known, the initial allocation of permits, $\widehat{e}_i$, does not have any effect on the firm's decision when the firm is a price taker in the permit market.

We next examine the market clearing condition for the good in the perfectly competitive industry. The total quantity produced (demanded) is denoted by $\widehat{Q} = \sum \widehat{q}_i$. Let $\widehat{S}(\widehat{Q})$ denote the inverse supply function of this industry when the environmental regulation is not in place yet. The inverse supply curve is the horizontal sum of the individual firms' marginal cost curves, $\widehat{C}_i'$, in the standard sense. Note that $\widehat{S}(\widehat{Q})$ is increasing since we assume that $\widehat{C}_i'' > 0$. $\widehat{P}(\widehat{Q})$ represents the inverse demand function for the product. We assume that $\widehat{P}' < 0$, that is, the inverse demand function is decreasing. The total initial permits allocated to this industry is denoted by $\widehat{e} = \sum \widehat{e}_i > 0$. Now the equilibrium condition for the good in the perfectly competitive industry is expressed as follows:

$$\widehat{P}(\widehat{Q}) = \widehat{S}(\widehat{Q}) + \widehat{r}P^e. \tag{4}$$

Given the permit price P^e, we obtain the equilibrium quantity $\widetilde{Q}(P^e)$ in the perfectly competitive industry by solving equation (4).[5] Obviously, if the permit price rises, the total quantity of good decreases, since each firm decreases its quantity as discussed above. This in turn decreases the total emissions of the pollutant from the perfectly competitive industry. Thus we have the following lemma:

Lemma 1 *The rise in the permit price leads to a reduction in the total quantity of good, and hence the total emissions of the pollutant in the perfectly competitive industry, that is,*

$$\widehat{r}\widetilde{Q}'(P^e) < 0. \tag{5}$$

Note that the rise in the permit price causes an increase in the product price in the perfectly competitive industry because the total quantity of good decreases.

2.3 Oligopolistic Industry

The oligopolistic industry supplies different product from the perfectly competitive industry. We consider a Cournot duopoly model, where firm $j = c, d$ competes in quantity. Firm j has a cost $C_j(q_j)$ of producing the quantity q_j. We assume that $C_j' > 0$ and $C_j'' > 0$. The total quantity produced (demanded) in this industry is denoted by $Q = \sum q_j$. Let $P(Q)$ denote

[5] Note that $\widehat{Q}(\widehat{P})$ represents the demand function for the product, while $\widetilde{Q}(P^e)$ is the equilibrium quantity in the perfectly competitive industry given the permit price P^e.

the inverse demand function for the product. We assume that $P' < 0$ and $P'' < 0$.

Let $r_j > 0$ denote each firm's emission rate of the pollutant. We assume that $r_c < r_d$, that is, firm c is relatively "clean," while firm d is relatively "dirty." Emission rates of the pollutant are assumed to be fixed during a given period of time as in the perfectly competitive industry. Emissions of each firm are proportional to its output, i.e., $r_j q_j$.

$e > 0$ represents the total initial permits allocated to the oligopolistic industry. Let $\alpha_j \in (0,1)$ denote the share of the initial permits issued to firm j, where $\sum \alpha_j = 1$. $\alpha_c e$ is initially issued to relatively "clean" firm c, while $\alpha_d e = (1 - \alpha_c)e$ is issued to relatively "dirty" firm d.

The total number of initial permits in both oligopolistic and perfectly competitive industries is $e + \widehat{e}$. All firms in both industries can trade their permits in the permit market. Recalling that the emissions of the pollutant from the perfectly competitive industry is expressed as $\widehat{r}\widetilde{Q}(P^e)$, we can write the market clearing condition for permits as follows:

$$\sum r_j q_j + \widehat{r}\widetilde{Q}(P^e) = e + \widehat{e}. \tag{6}$$

From equation (6), we obtain the market clearing permit price as a function of the output produced in the oligopolistic industry, i.e., $P^e(q)$, where q denotes the output vector (q_j, q_{-j}). It should be noted that the firms in the oligopolistic industry have market power in the permit market in the sense that they can affect the permit price through their choices of output level. Suppose that firm j increases its output q_j, and hence its emissions $r_j q_j$, with another firm's output q_{-j} remaining unchanged. Then, the emissions from the perfectly competitive industry, $\widehat{r}\widetilde{Q}(P^e)$, must decrease so that equation (6) is satisfied. Thus, it follows from Lemma 1 that the permit price P^e must rise. We can state this result formally by considering the implicit relationship $F(q, P^e) \equiv \sum r_j q_j + \widehat{r}\widetilde{Q}(P^e) - e - \widehat{e} = 0$. From the implicit function theorem and Lemma 1, we have

$$\frac{\partial P^e}{\partial q_j} = -\frac{\frac{\partial F}{\partial q_j}}{\frac{\partial F}{\partial P^e}} = -\frac{r_j}{\widehat{r}\widetilde{Q}'(P^e)} > 0. \tag{7}$$

Moreover, note that the following holds:

$$\frac{\partial^2 P^e}{\partial q_j^2} = 0, \ \frac{\partial^2 P^e}{\partial q_{-j} \partial q_j} = 0. \tag{8}$$

We now describe the profit maximization problem of the duopolist j who has market power in the permit market as well as in its product market:

$$\max_{q_j} \ \Pi_j = P(Q)q_j - C_j(q_j) - P^e(q)\left(r_j q_j - \alpha_j e\right) \tag{9}$$

$$\text{s.t.}$$

$$q_j \geq 0. \tag{10}$$

Firm j's overall profit Π_j is represented by its profit in the product market, $P(Q)q_j - C_j(q_j)$, and its net expense of tradable permits, $P^e(q)\left(r_j q_j - \alpha_j e\right)$. Note that each firm can affect not only the product price $P(Q)$ but also the permit price $P^e(q)$ through its decision of output level q_j. Here, the tradable permit system is in effect equivalent to a "tax and subsidy" system as in the case of the perfectly competitive industry. However, it is different from the case in Subsection 2.2 in the sense that each firm can manipulate the "tax" $P^e(q)r_j q_j$ and "subsidy" $P^e(q)\alpha_j e$ through the permit price $P^e(q)$.

Assuming an interior solution, we can then characterize firm j's decision on output by the first order condition $\frac{\partial \Pi_j}{\partial q_j} = 0$. We have the following:

$$P(Q) + P'(Q)q_j = C_j'(q_j) + r_j\left(P^e(q) + \frac{\partial P^e(q)}{\partial q_j}q_j\right) - \frac{\partial P^e(q)}{\partial q_j}\alpha_j e. \tag{11}$$

The LHS of equation (11) represents the marginal revenue from the product market. The RHS consists of three components. The first term is the marginal cost of production. The second term can be interpreted as a "marginal tax," which is an additional cost incurred through the tradable permit system. Note that $r_j\left(P^e(q) + \frac{\partial P^e(q)}{\partial q_j}q_j\right) > 0$ since $\frac{\partial P^e}{\partial q_j}$ is positive from (7). It has the effect of raising the overall marginal cost, and hence decreasing the output q_j. In contrast, the third term, $-\frac{\partial P^e(q)}{\partial q_j}\alpha_j e < 0$, can be interpreted as a "marginal subsidy," which stems from the initial permits allocated to the firm. It has the effect of lowering the overall marginal cost, and hence increasing the output q_j. What is important is that the initial allocation of permits, $\alpha_j e$, does affect the firm's decision when the firm has market power in the permit market. This result is contrary to the well-known result that the initial allocation of permits does not have any effect on firms' decisions when the firms are price takers in the permit market. We will examine the effects of initial allocation in more detail in the next section.

Before turning to the analysis of initial allocation, we show that the actions of the two firms are strategic substitutes. For this purpose, we show that $\frac{\partial^2 \Pi_j}{\partial q_{-j} \partial q_j} < 0$.[6] A simple calculation yields

$$\frac{\partial^2 \Pi_j}{\partial q_{-j} \partial q_j} = P' + P'' q_j - r_j \frac{\partial P^e}{\partial q_{-j}} - \frac{\partial^2 P^e}{\partial q_{-j} \partial q_j} \left(r_j q_j - \alpha_j e \right). \tag{12}$$

It follows from (7) and the assumptions regarding the demand for the product that the first three terms on the RHS of (12) are negative. Moreover, it follows from (8) that the last term on the RHS equals zero. Thus $\frac{\partial^2 \Pi_j}{\partial q_{-j} \partial q_j}$ is negative. We can summarize this result in the following lemma:

Lemma 2 *The firms' outputs in the oligopolistic industry are strategic substitutes:*

$$\frac{\partial^2 \Pi_j}{\partial q_{-j} \partial q_j} < 0. \tag{13}$$

Lemma 2 implies that each firm's best response curve is downward sloping as in a standard Cournot game. From firm j's first order condition, we obtain its best response function $q_j = R_j(q_{-j}, \alpha_j)$, where the share of the initial permits, α_j, is a parameter decided by the regulatory authority. Applying the implicit function theorem to the first order condition $\frac{\partial \Pi_j}{\partial q_j} = 0$, we obtain the partial derivative of firm j's best response function R_j with respect to the opponent's quantity q_{-j}:

$$\frac{\partial R_j}{\partial q_{-j}} = -\frac{\frac{\partial^2 \Pi_j}{\partial q_{-j} \partial q_j}}{\frac{\partial^2 \Pi_j}{\partial q_j^2}} < 0, \tag{14}$$

with $\frac{\partial^2 \Pi_j}{\partial q_j^2} = 2P' + P'' q_j - C_j'' - 2 r_j \frac{\partial P^e}{\partial q_j} - \frac{\partial^2 P^e}{\partial q_j^2} \left(r_j q_j - \alpha_j e \right) < 0$. Note that $\frac{\partial^2 \Pi_j}{\partial q_j^2} < 0$ is obtained from (7), (8), and the assumptions regarding the demand and cost.

Consequently, the Cournot-Nash equilibrium occurs where the downward-sloping best response curves intersect. We further make the assumption that

[6] For a detailed discussion of strategic substitutes, see Bulow et al. (1985) and Tirole (1988, p. 207).

the following condition for the local stability of the equilibrium holds as in a standard Cournot game:[7]

$$\frac{\partial^2\Pi_j}{\partial q_j^2}\frac{\partial^2\Pi_{-j}}{\partial q_{-j}^2} > \frac{\partial^2\Pi_j}{\partial q_{-j}\partial q_j}\frac{\partial^2\Pi_{-j}}{\partial q_j\partial q_{-j}}. \tag{15}$$

The condition (15) implies that the slope of firm j's best response curve is steeper than that of firm $-j$'s, when we take q_j as the horizontal axis and q_{-j} as the vertical axis.[8] This ensures the local stability of the Cournot-Nash equilibrium.

3 Effects of the Initial Permit Allocation

3.1 Impact on the Firm's Decision

We investigate the effects of the initial permit allocation on the equilibrium outcomes. Specifically, our focus is on the impacts of changing α_j, that is, the allocation between relatively "clean" and "dirty" firms in the oligopolistic industry.

Let us first demonstrate how the initial allocation of permits affects the firm's output decision in the oligopolistic industry, by examining each firm's best response function. Suppose that the regulatory authority raises firm j's share of the initial permits, while lowering firm $-j$'s share; that is, the regulator increases α_j, which in turn leads to a reduction in $\alpha_{-j} = 1 - \alpha_j$. Applying the implicit function theorem to firm j's first order condition $\frac{\partial\Pi_j}{\partial q_j} = 0$, we obtain the partial derivative of j's best response function $q_j = R_j(q_{-j}, \alpha_j)$ with respect to the initial allocation α_j:

$$\frac{\partial R_j}{\partial \alpha_j} = -\frac{\frac{\partial^2\Pi_j}{\partial\alpha_j\partial q_j}}{\frac{\partial^2\Pi_j}{\partial q_j^2}} = -\frac{\frac{\partial P^e(q)}{\partial q_j}e}{\frac{\partial^2\Pi_j}{\partial q_j^2}} > 0, \tag{16}$$

with $\frac{\partial P^e(q)}{\partial q_j} > 0$ and $\frac{\partial^2\Pi_j}{\partial q_j^2} < 0$ as discussed in the previous section. Thus, for any given q_{-j}, q_j increases as α_j is raised. On the other hand, using

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[7] See, for example, Tirole (1988, p. 324).

[8] We have $\left|\frac{\partial R_j^{-1}}{\partial q_j}\right| = \frac{\frac{\partial^2\Pi_j}{\partial q_j^2}}{\frac{\partial^2\Pi_j}{\partial q_{-j}\partial q_j}} > \frac{\frac{\partial^2\Pi_{-j}}{\partial q_j\partial q_{-j}}}{\frac{\partial^2\Pi_{-j}}{\partial q_{-j}^2}} = \left|\frac{\partial R_{-j}}{\partial q_j}\right|$, where R_j^{-1} represents the inverse function of R_j.

$\alpha_{-j} = 1 - \alpha_j$, we can express firm $-j$'s first order condition as $\frac{\partial \Pi_{-j}}{\partial q_{-j}} = P + P' q_{-j} - C'_{-j} - r_{-j}\left(P^e + \frac{\partial P^e}{\partial q_{-j}} q_{-j}\right) + \frac{\partial P^e}{\partial q_{-j}}(1-\alpha_j)e = 0$. Applying the implicit function theorem to firm $-j$'s first order condition $\frac{\partial \Pi_{-j}}{\partial q_{-j}} = 0$, we obtain the partial derivative of $-j$'s best response function $q_{-j} = R_{-j}(q_j, \alpha_j)$ with respect to the initial allocation α_j:

$$\frac{\partial R_{-j}}{\partial \alpha_j} = -\frac{\frac{\partial^2 \Pi_{-j}}{\partial \alpha_j \partial q_{-j}}}{\frac{\partial^2 \Pi_{-j}}{\partial q_{-j}^2}} = -\frac{-\frac{\partial P^e(q)}{\partial q_{-j}} e}{\frac{\partial^2 \Pi_{-j}}{\partial q_{-j}^2}} < 0, \tag{17}$$

with $\frac{\partial P^e(q)}{\partial q_{-j}} > 0$ and $\frac{\partial^2 \Pi_{-j}}{\partial q_{-j}^2} < 0$. Thus, for any given q_j, q_{-j} decreases as α_j is raised (i.e., α_{-j} is reduced).

It follows from (16) that firm j's best response curve shifts outward as its share of the initial permits, α_j, rises. This is because raising α_j has the effect of increasing firm j's "marginal subsidy" expressed in equation (11), and in turn reducing the overall marginal cost. In contrast, (17) implies that firm $-j$'s best response curve shifts inward as its share of the initial permits, α_{-j}, decreases. This is because lowering α_{-j} has the effect of decreasing firm $-j$'s "marginal subsidy," and in turn increasing the overall marginal cost. Recall that Lemma 2 demonstrates that each firm's best response curve is downward sloping. Recall also that the condition (15) implies that the slope of firm j's best response curve is steeper than that of firm $-j$'s, when we take q_j as the horizontal axis and q_{-j} as the vertical axis. Then, raising α_j has the effects of increasing firm j's equilibrium output, while decreasing firm $-j$'s equilibrium output, as illustrated in Figure 1.

[Figure 1 about here]

We now formally state the effects of the initial permit allocation α_j on the equilibrium output $q^* = (q_j^*, q_{-j}^*)$ in the following proposition:

Proposition 1 *Suppose that the regulator raises firm j's share of the initial permits, α_j, in the oligopolistic industry. Then, in equilibrium, firm j increases its output q_j^*, while firm $-j$ decreases its output q_{-j}^*, that is,*

$$\frac{dq_j^*}{d\alpha_j} > 0, \;\; \frac{dq_{-j}^*}{d\alpha_j} < 0. \tag{18}$$

It should be emphasized that the initial allocation of permits affects the firm's decision, and hence equilibrium, when the firm has market power in the permit market. The greater the number of initial permits allocated to firm j, the larger the output produced by that firm in equilibrium (regardless of whether the firm is "clean" or "dirty"). As discussed above, this is because raising α_j has the effect of increasing firm j's "marginal subsidy" expressed in (11), and in turn reducing the overall marginal cost. The result in Proposition 1 is contrary to the well-known result that the initial allocation of permits does not have any effect on the firm's decision and equilibrium when the firm is a price taker in the permit market.

3.2 Permit and Product Prices

We next demonstrate the effects of the initial permit allocation on the equilibrium prices—the equilibrium permit price and the equilibrium product prices in both oligopolistic and perfectly competitive industries.

Suppose here that the regulatory authority raises "clean" firm c's share of the initial permits, α_c, while lowering "dirty" firm d's share, $\alpha_d = 1 - \alpha_c$. Then, the changes in the equilibrium output in the oligopolistic industry can be expressed as $\Delta q_c^* \equiv \frac{dq_c^*}{d\alpha_c} > 0$ and $\Delta q_d^* \equiv \frac{dq_d^*}{d\alpha_c} < 0$ from Proposition 1.

If the ratio of the change in q_d^* to the change in q_c^* in absolute value is less than 1, i.e., $-\frac{\Delta q_d^*}{\Delta q_c^*} < 1$, then the total equilibrium quantity produced in the oligopolistic industry obviously increases, i.e., $\Delta q_c^* + \Delta q_d^* = \Delta Q^* > 0$. This in turn leads to a reduction in the equilibrium product price $P^* = P(Q^*)$ in the oligopolistic industry. In contrast, if $1 < -\frac{\Delta q_d^*}{\Delta q_c^*}$, then the total equilibrium quantity decreases, which in turn leads to a rise in the equilibrium product price, P^*, in this industry.

On the other hand, if the ratio of the change in q_d^* to the change in q_c^* in absolute value is greater than the ratio of emission rates, $\frac{r_c}{r_d}$, i.e., $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*}$, then the total equilibrium emissions in the oligopolistic industry decreases, i.e., $r_c \Delta q_c^* + r_d \Delta q_d^* < 0$. Recall the market clearing condition for permits, $r_c q_c + r_d q_d + \widehat{r}\widetilde{Q}(P^e) = e + \widehat{e}$, in equation (6). As the total number of initial permits in both industries is given, the reduction in the total emissions in the oligopolistic industry allows the increase in the total emissions in the perfectly competitive industry. Therefore, noting that $\widehat{r}\widetilde{Q}'(P^e) < 0$ from Lemma 1, the equilibrium permit price P^{e*} decreases. Moreover, it is worth noting that the total equilibrium quantity $\widehat{Q}^* = \widetilde{Q}(P^{e*})$ increases, which in turn leads to a reduction in the equilibrium product price, $\widehat{P}^* = \widehat{P}(\widehat{Q}^*)$, in the perfectly competitive industry. In contrast, we can easily verify that if $-\frac{\Delta q_d^*}{\Delta q_c^*} < \frac{r_c}{r_d}$, both P^{e*} and $\widehat{P}^*$ rise.

We can now summarize the effects of raising "clean" firm c's share of the initial permits, α_c, on the equilibrium prices, P^{e*}, $\widehat{P}^*$ and P^*, in the following proposition:

Proposition 2 *Suppose that the regulator raises "clean" firm c's share of the initial permits, α_c. Then,*
(i) *if* $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*} < 1$ *holds,* P^{e*}*,* $\widehat{P}^*$ *and* P^* *fall,*
(ii) *if* $1 < -\frac{\Delta q_d^*}{\Delta q_c^*}$ *holds,* P^{e*} *and* $\widehat{P}^*$ *fall, while* P^* *rises,*
(iii) *if* $-\frac{\Delta q_d^*}{\Delta q_c^*} < \frac{r_c}{r_d}$ *holds,* P^{e*} *and* $\widehat{P}^*$ *rise, while* P^* *falls.*

It should be stressed that raising the "clean" firm's share of the initial permits can lower the prices in both oligopolistic and perfectly competitive industries under certain conditions. Case (i) in Proposition 2 implies that if the increase in q_c^* is not too large compared to the reduction in q_d^* (i.e, $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*}$), the total emissions in the oligopolistic industry is likely to decrease. This in turn allows the perfectly competitive industry to emit more, with the reduction in the permit price P^{e*}. Moreover, as the emissions increase is due to the increase in the total quantity produced in the perfectly competitive industry, the product price $\widehat{P}^*$ in this industry falls. Case (i) also implies that if the increase in q_c^* is larger than the reduction in q_d^* in magnitude (i.e., $-\frac{\Delta q_d^*}{\Delta q_c^*} < 1$), the total quantity produced in the oligopolistic industry increases. This in turn leads to a decrease in the product price P^* in this industry.

The demand and cost structures in both industries determine which outcome in Proposition 2 actually occurs. In order to examine further conditions, we restrict ourselves to the specific case of linear demand and constant marginal cost, focusing on case (i) in Proposition 2. The inverse demand functions for the oligopolistic and perfectly competitive industries are given by $P = a - bQ$ and $\widehat{P} = \widehat{a} - \widehat{b}\widehat{Q}$, respectively. The "clean" and "dirty" firms in the oligopolistic industry have constant marginal costs of c_c and c_d, respectively. The inverse supply function for the perfectly competitive industry (before the introduction of environmental regulation) is given by a constant $\widehat{c}$. All parameters are assumed to be positive. Then, we have the following proposition:

Proposition 3 *Suppose that the regulator raises "clean" firm c's share of the initial permits,* α_c*. Then, if* $\frac{b}{\hat{b}} < \frac{3r_c r_d}{\hat{r}^2}$ *is satisfied,* $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*} < 1$ *holds, and hence* P^{e*}*,* $\widehat{P}^*$ *and* P^* *fall.*

The proof is given in Appendix A. Proposition 3 implies that in the case of linear demand and constant marginal cost, the relationship between the demand factor and the emission rate is the key for case (i) in Proposition 2 to take place.[9]

In contrast to Proposition 2, we can expect the reverse effects when lowering the "clean" firm's share of the initial permits. Suppose that the regulatory authority lowers "clean" firm c's share of the initial permits, α_c, while raising "dirty" firm d's share, $\alpha_d = 1 - \alpha_c$. Then, the changes in the equilibrium output in the oligopolistic industry can be expressed as $\Delta q_c^* \equiv -\frac{dq_c^*}{d\alpha_c} < 0$ and $\Delta q_d^* \equiv -\frac{dq_d^*}{d\alpha_c} > 0$ from Proposition 1. Note that the signs of Δq_c^* and Δq_d^* are the reverse of those in Proposition 2.

If $-\frac{\Delta q_d^*}{\Delta q_c^*} < 1$ holds, then we have $\Delta q_c^* + \Delta q_d^* = \Delta Q^* < 0$, noting that $\Delta q_c^* < 0$. This in turn leads to a rise in the equilibrium product price P^* in the oligopolistic industry. Note that if $1 < -\frac{\Delta q_d^*}{\Delta q_c^*}$, then P^* decreases.

On the other hand, if $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*}$ holds, then we have $r_c \Delta q_c^* + r_d \Delta q_d^* > 0$. The increase in the total emissions in the oligopolistic industry implies a reduction in the total emissions in the perfectly competitive industry. This results in a rise in both the equilibrium permit price P^{e*} and the equilibrium product price $\widehat{P}^*$ in the perfectly competitive industry. Note that if $-\frac{\Delta q_d^*}{\Delta q_c^*} < \frac{r_c}{r_d}$, both P^{e*} and $\widehat{P}^*$ fall.

We can now summarize these reverse effects in the following corollary of Proposition 2:

Corollary 1 *Suppose that the regulator lowers "clean" firm c's share of the initial permits,* α_c*. Then,*
(i) *if* $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*} < 1$ *holds,* P^{e*}*,* $\widehat{P}^*$ *and* P^* *rise,*
(ii) *if* $1 < -\frac{\Delta q_d^*}{\Delta q_c^*}$ *holds,* P^{e*} *and* $\widehat{P}^*$ *rise, while* P^* *falls,*
(iii) *if* $-\frac{\Delta q_d^*}{\Delta q_c^*} < \frac{r_c}{r_d}$ *holds,* P^{e*} *and* $\widehat{P}^*$ *fall, while* P^* *rises.*

[9] In the case of linear demand and linear marginal cost, the cost factor also plays a key role, and the condition associated with the relationship between the demand factor, the cost factor, and the emission rate becomes more complex.

Corollary 1 implies that a simultaneous decrease in prices in both oligopolistic and perfectly competitive industries cannot be achieved by lowering the "clean" firm's share of the initial permits. As described in case (ii) in Corollary 1, if $1 < -\frac{\Delta q_d^*}{\Delta q_c^*}$ holds, then P^* falls. For $1 < -\frac{\Delta q_d^*}{\Delta q_c^*}$ to be satisfied, the increase in q_d^* must be larger than the reduction in q_c^* in magnitude. However, this does not coincide with the condition $-\frac{\Delta q_d^*}{\Delta q_c^*} < \frac{r_c}{r_d}(< 1)$ in (iii), which ensures the reduction in $\widehat{P}^*$.

3.3 Social Welfare

Changing the allocation of permits may lead to a trade-off in terms of social welfare. Indeed, cases (ii) and (iii) in Proposition 2 show that the product price in one industry decreases while the product price increases in another industry. Moreover, there may be a trade-off even in the attractive case of (i) in Proposition 2, where raising the "clean" firm's share of the initial permits can lower the prices in both oligopolistic and perfectly competitive industries. The "clean" firm may have a higher production cost than the "dirty" firm. For example, a natural gas-fired power plant with a low emission rate of pollutant ("clean" plant) generally has a higher production cost than a coal-fired power plant with a high emission rate ("dirty" plant). In such a case, raising the "clean" firm's share of the initial permits increases the production inefficiency in the oligopolistic industry since the "clean" firm with a high production cost increases its output. Thus, even in case (i) in Proposition 2, we may observe a trade-off between production inefficiency and consumer benefit.

Considering this trade-off caused by the permit allocation, we can characterize the interior solution for the socially optimal allocation $\alpha_c^* \in (0, 1)$. Let us first define social welfare as the sum of social surplus in each industry in equilibrium:

$$SW = \int_0^{Q^*} P(Q)dQ - C_c(q_c^*) - C_d(q_d^*) + \int_0^{\widehat{Q}^*} \widehat{P}(\widehat{Q})d\widehat{Q} - \int_0^{\widehat{Q}^*} \widehat{S}(\widehat{Q})d\widehat{Q}. \quad (19)$$

Note that the net expenses of tradable permits do not appear in (19) since they are netted out.

The regulatory authority seeks to maximize social welfare expressed in (19), by changing the allocation of permits. Assuming an interior solution, the first order condition, $\frac{\partial SW}{\partial \alpha_c} = 0$, characterizes the socially optimal allocation of permits. Thus, the following proposition is straightforward:

Proposition 4 *At any optimal allocation $\alpha_c^* \in (0,1)$, the change in social surplus in the oligopolistic industry associated with a unit change in the permit allocation is balanced with that in the perfectly competitive industry. That is,*

$$P(Q^*)\frac{dQ^*}{d\alpha_c} - C_c'(q_c^*)\frac{dq_c^*}{d\alpha_c} - C_d'(q_d^*)\frac{dq_d^*}{d\alpha_c} = -\left(\widehat{P}(\widehat{Q}^*) - \widehat{S}(\widehat{Q}^*)\right)\frac{d\widehat{Q}^*}{d\alpha_c}. \quad (20)$$

Specifically, we focus on the attractive case of (i) in Proposition 2, where increasing the "clean" firm's share of the initial permits can decrease the prices in both industries. As discussed in Subsection 3.2, we have $\frac{dq_c^*}{d\alpha_c} > 0$, $\frac{dq_d^*}{d\alpha_c} < 0$, $\frac{dQ^*}{d\alpha_c} > 0$ and $\frac{d\widehat{Q}^*}{d\alpha_c} > 0$ in the case of (i). Moreover, the equilibrium condition (4) for the product in the perfectly competitive industry implies that $\widehat{P}(\widehat{Q}^*) > \widehat{S}(\widehat{Q}^*)$ for any $P^{e*} > 0$. Thus, the signs of the terms in equation (20) are as follows:

$$\underbrace{P^*\frac{dQ^*}{d\alpha_c}}_{+} - \underbrace{C_c'(q_c^*)\frac{dq_c^*}{d\alpha_c}}_{+} - \underbrace{C_d'(q_d^*)\frac{dq_d^*}{d\alpha_c}}_{-} = -\underbrace{\left(\widehat{P}^* - \widehat{S}^*\right)\frac{d\widehat{Q}^*}{d\alpha_c}}_{+}. \quad (21)$$

In case (i) in Proposition 2, social surplus in the perfectly competitive industry increases by raising the "clean" firm's share of the initial permits.[10] On the other hand, if the "clean" firm has a cost disadvantage compared to the "dirty" firm, raising the "clean" firm's share of the permits would increase the production inefficiency in the oligopolistic industry. Furthermore, the increase in the production inefficiency may outweigh the increase in the consumer benefit obtained from the product price reduction in the oligopolistic industry. Consequently, as depicted in (21), the socially optimal allocation of permits would be such that the reduction in social surplus in the oligopolistic industry associated with a unit change in the permit allocation, i.e., $P^*\frac{dQ^*}{d\alpha_c} - C_c'(q_c^*)\frac{dq_c^*}{d\alpha_c} - C_d'(q_d^*)\frac{dq_d^*}{d\alpha_c} < 0$, is balanced with the increase in social surplus in the perfectly competitive industry, i.e., $\left(\widehat{P}^* - \widehat{S}^*\right)\frac{d\widehat{Q}^*}{d\alpha_c} > 0$.[11] We will illustrate this result using a numerical example in the next section.

[10] Note that there is no production inefficiency because marginal production costs are equalized among firms in the perfectly competitive industry.

[11] Extreme cases can also be considered at least in theory. If the cost disadvantage of the

4 Numerical Example

We consider the case of linear demand and constant marginal cost discussed in Subsection 3.2. The inverse demand functions for the oligopolistic and perfectly competitive industries are given by $a - bQ = 100 - 0.01Q$ and $\widehat{a} - \widehat{b}\widehat{Q} = 200 - 0.02\widehat{Q}$, respectively. In the oligopolistic industry, the marginal cost and emission rate of "clean" firm c are $c_c = 40$ and $r_c = 0.3$, respectively, while those of "dirty" firm d are $c_d = 20$ and $r_d = 0.9$, respectively. Thus, the "clean" firm with a low emission rate of pollutant (e.g., natural gas-fired generator) has a higher production cost than the "dirty" firm with a high emission rate (e.g., coal-fired generator). In the perfectly competitive industry, the inverse supply function (before the introduction of environmental regulation) and emission rate are $\widehat{c} = 30$ and $\widehat{r} = 0.5$, respectively. The number of permits initially assigned to the oligopolistic and perfectly competitive industries are given by $e = 2,720$ and $\widehat{e} = 3,400$, respectively.[12]

Note that the condition in Proposition 3 is satisfied, given the parameters above. Therefore, raising the "clean" firm's share of the initial permits leads to a reduction in the permit and product prices as illustrated in Figure 2. Figure 3 shows the actual emissions from both industries. In this example, raising the share of the "clean" firm reduces the total emissions in the oligopolistic industry since the increase in the output and emissions of firm c are not too large compared to the reduction in those of firm d. This in turn allows the perfectly competitive industry to emit more, with the reduction in the permit price.

[Figure 2 about here]
[Figure 3 about here]

"clean" firm is extremely large, it might be optimal to allocate no permits to the "clean" firm; that is $\alpha_c^* = 0$. In this case, $\frac{\partial SW}{\partial \alpha_c} < 0$ holds at $\alpha_c^* = 0$. In contrast, if the cost disadvantage of the "clean" firm is sufficiently small, and hence production inefficiency is negligible, it might be optimal to allocate all of the permits to the "clean" firm; that is $\alpha_c^* = 1$. In this case, $\frac{\partial SW}{\partial \alpha_c} > 0$ holds at $\alpha_c^* = 1$.

[12] We first calculate the actual emissions from both industries before considering the introduction of environmental regulation. Then, assuming a 20 percent reduction of emissions from these historical emission levels, we calculate the number of permits initially assigned to each industry.

Figure 4 illustrates social welfare as the sum of social surplus in each industry. In the perfectly competitive industry, raising the "clean" firm's share of the initial permits increases social surplus, along with the reduction in the product price. On the other hand, in the oligopolistic industry, the production inefficiency gradually increases since the "clean" firm has a cost disadvantage compared to the "dirty" firm. After all, the increase in the production inefficiency outweighs the increase in the consumer benefit obtained from the product price reduction in the oligopolistic industry. Consequently, the socially optimal allocation of permits is such that the reduction in social surplus in the oligopolistic industry is balanced with the increase in social surplus in the perfectly competitive industry, as illustrated in Figure 4. In this example, it is socially optimal to allocate 60 percent of the initial permits to the "clean" firm.

[Figure 4 about here]

5 Concluding Remarks

This paper has examined a multi-sector model of tradable emission permits, where the firms in the oligopolistic industry can exercise market power in the tradable permit market as well as in the product market, while those in the perfectly competitive industry are price takers in the permit market. Specifically, we have examined the effects of the initial permit allocation on the equilibrium outcomes, focusing on the interaction among these product and permit markets. We have shown that raising the number of initial permits allocated to one firm in the oligopolistic industry increases the output produced by that firm since the initial distribution of permits serves as a subsidy. Under certain conditions, raising the "clean" (less-polluting) firm's share of the initial permits can lower not only the permit price but also the product prices in both oligopolistic and perfectly competitive industries simultaneously. It should be noted that a simultaneous decrease in prices in both oligopolistic and perfectly competitive industries cannot be achieved by lowering the "clean" firm's share of the initial permits. Moreover, we have discussed criteria for the socially optimal allocation of initial permits, considering the trade-off between production inefficiency and consumer benefit. The socially optimal allocation of permits is such that the change in social surplus in the oligopolistic industry associated with a unit change in the permit allocation is balanced with that in the perfectly competitive industry.

The optimal allocation of initial permits depends on the demand and cost structures. Thus, further work conducting simulations based on real market data would be of interest from a practical point of view. Another avenue for future research would be to compare the effects of tradable emission permits with those of Pigouvian taxes within the current multi-sector model. Further work should aim to compare the grandfathering scheme and the auction of the permits within the current model.

Appendix A

Proof of Proposition 3

The equilibrium condition (4) for the good in the perfectly competitive industry is rewritten as:

$$\widehat{a} - \widehat{b}\widehat{Q} = \widehat{c} + \widehat{r}P^e. \tag{22}$$

By solving equation (22), we have the equilibrium quantity $\widetilde{Q}(P^e) = \frac{\widehat{a}-\widehat{c}-\widehat{r}P^e}{\widehat{b}}$ in this industry. We can next rewrite the market clearing condition for permits, (6), as follows:

$$\sum r_j q_j + \frac{\widehat{r}\left(\widehat{a} - \widehat{c} - \widehat{r}P^e\right)}{\widehat{b}} = e + \widehat{e}. \tag{23}$$

From equation (23), we have the market clearing permit price as a function of the output produced in the oligopolistic industry:

$$P^e(q) = \frac{\widehat{b}\left(\sum r_j q_j - e - \widehat{e}\right) + \widehat{r}\left(\widehat{a} - \widehat{c}\right)}{\widehat{r}^2}. \tag{24}$$

In the oligopolistic industry, the following holds in equilibrium:

$$\frac{\partial \Pi_c(q_c^*(\alpha_c), q_d^*(\alpha_c), \alpha_c)}{\partial q_c} = 0, \tag{25}$$

$$\frac{\partial \Pi_d(q_c^*(\alpha_c), q_d^*(\alpha_c), \alpha_c)}{\partial q_d} = 0. \tag{26}$$

By differentiating equations (25) and (26) with respect to α_c, and applying Cramer's rule, we can obtain $\Delta q_c^* \equiv \frac{dq_c^*}{d\alpha_c}$ and $\Delta q_d^* \equiv \frac{dq_d^*}{d\alpha_c}$. Then, recalling equation (24), $\frac{\Delta q_d^*}{\Delta q_c^*}$ can be derived as follows:

$$\frac{\Delta q_d^*}{\Delta q_c^*} = \frac{\frac{\partial^2 \Pi_d}{\partial q_c \partial q_d}\frac{\partial^2 \Pi_c}{\partial \alpha_c \partial q_c} - \frac{\partial^2 \Pi_c}{\partial q_c^2}\frac{\partial^2 \Pi_d}{\partial \alpha_c \partial q_d}}{\frac{\partial^2 \Pi_c}{\partial q_d \partial q_c}\frac{\partial^2 \Pi_d}{\partial \alpha_c \partial q_d} - \frac{\partial^2 \Pi_d}{\partial q_d^2}\frac{\partial^2 \Pi_c}{\partial \alpha_c \partial q_c}}$$
$$= -\frac{3\widehat{b}r_c^2 r_d + b\widehat{r}^2 (r_c + 2r_d)}{3\widehat{b}r_c r_d^2 + b\widehat{r}^2 (2r_c + r_d)}. \tag{27}$$

Recalling that $r_c < r_d$ and all parameters are positive by assumption, we have:

$$\frac{r_c}{r_d} + \frac{\Delta q_d^*}{\Delta q_c^*} = \frac{2b\widehat{r}^2 (r_c^2 - r_d^2)}{3\widehat{b}r_c r_d^3 + b\widehat{r}^2 r_d (2r_c + r_d)} < 0. \tag{28}$$

Thus, $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*}$ holds. Next, we have:

$$1 + \frac{\Delta q_d^*}{\Delta q_c^*} = \frac{(r_c - r_d)\left(b\widehat{r}^2 - 3\widehat{b}r_c r_d\right)}{3\widehat{b}r_c r_d^2 + b\widehat{r}^2 (2r_c + r_d)}. \tag{29}$$

Thus, if $\frac{b}{\widehat{b}} < \frac{3r_c r_d}{\widehat{r}^2}$, then (29) is positive and $-\frac{\Delta q_d^*}{\Delta q_c^*} < 1$ holds. Putting all together, if $\frac{b}{\widehat{b}} < \frac{3r_c r_d}{\widehat{r}^2}$ is satisfied, $\frac{r_c}{r_d} < -\frac{\Delta q_d^*}{\Delta q_c^*} < 1$ holds, and hence P^{e*}, $\widehat{P}^*$ and P^* fall from Proposition 2. ■

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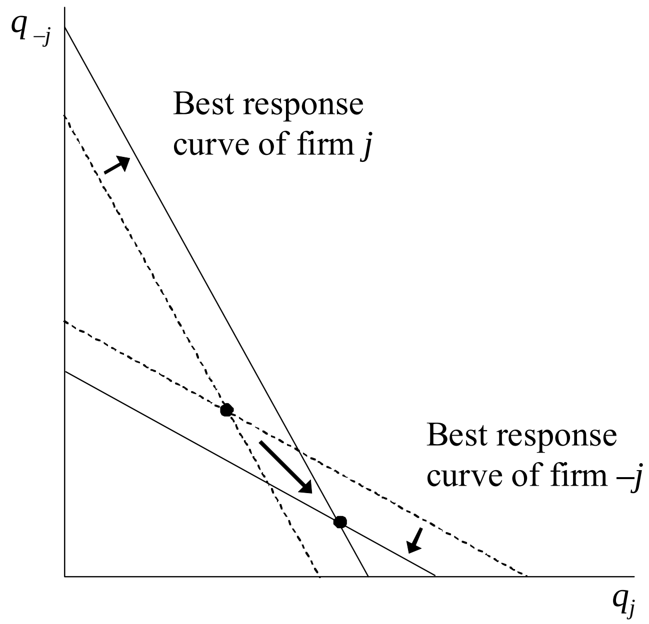

Figure 1: Effects on the firm's output decision

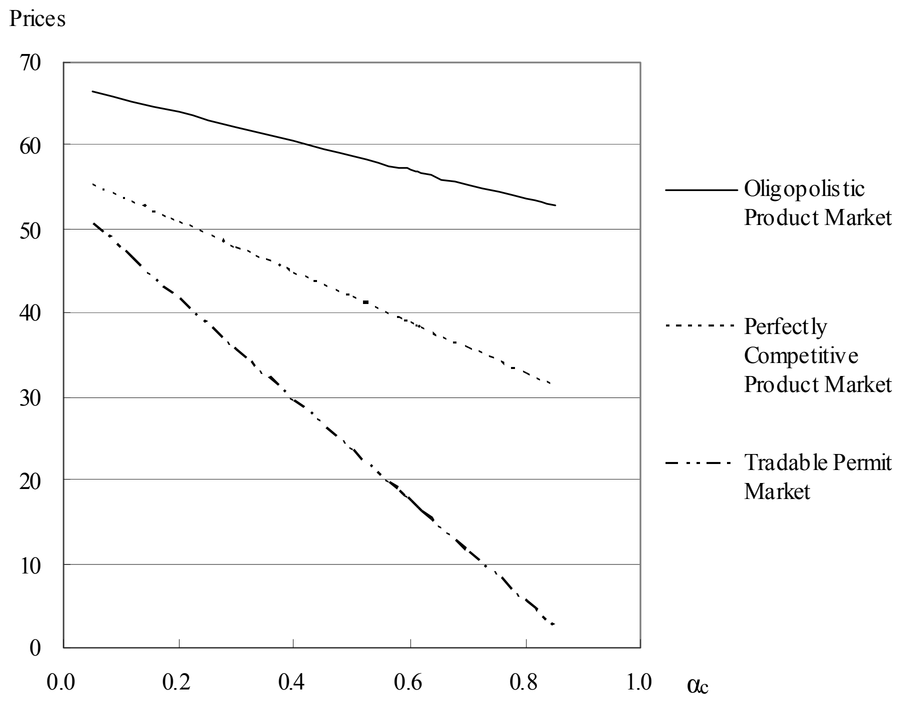

Figure 2: Changes in the permit and product prices

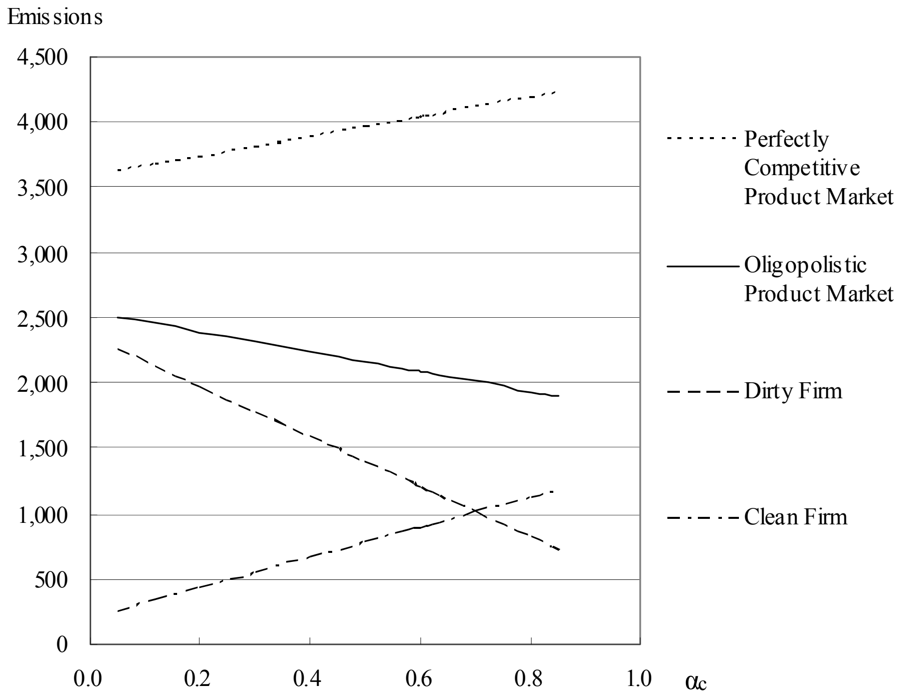

Figure 3: Changes in the emissions

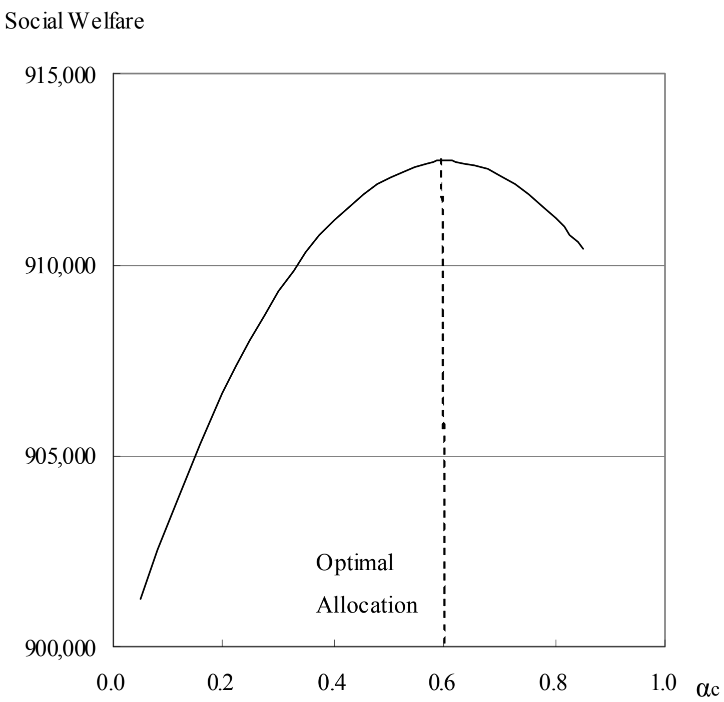

Figure 4: Socially optimal allocation of permits