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Permit Trading and Credit Trading
A Comparison of Cap-Based and Rate-Based Emissions Trading under Perfect and Imperfect Competition*

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Abstract

This paper compares emissions trading based on a cap on total emissions (permit trading) and on relative standards per unit of output (credit trading). Two types of market structure are considered: perfect competition and Cournot oligopoly. The effect of combining the two schemes is also discussed.

We find that output and abatement costs are higher under credit trading. Combining the two schemes may give an increase in welfare. With perfect competition, permit trading always leads to higher welfare than credit trading. With imperfect competition, credit trading may outperform permit trading.

Environmental policy can lead to both entry and exit of firms. Entry and exit have a profound impact on the performance of the schemes, especially under imperfect competition. We find that it may be impossible to implement certain levels of total industry emissions. Under credit trading several levels of the relative standard can achieve the same total level of emissions.

Keywords: emissions trading, entry and exit, permit allocation, tradable performance standards

JEL classification: H23, H3, Q48, Q52, Q58

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1 Introduction

In the economic literature, emissions trading is almost always equated with a system based on a ceiling or cap on total emissions. In such a scheme, the government agency determines a cap on total emissions and divides this into permits that are distributed among the incumbent firms, after which the firms are allowed to trade the permits. The first large-scale application of such a scheme was the US SO_2 trading scheme that started in 1995 (see Schmalensee et al. 1998). Currently, the largest cap-and-trade system is the EU greenhouse gas emissions allowances trading scheme that started on 1 January 2005 (DIR 2003/87/EC).

Before cap-and-trade, or permit trading, schemes had started, another type of emissions trading had been developed in the US and formalized in the EPA emissions trading program. This system is based on a relative emission standard that sets a maximum level of emissions per unit of some input or output. Firms that succeed in keeping their emissions below the level required by the emission standard receive emission reduction credits. They can sell them to other firms that are then allowed to emit more than the level defined by the emission standard. The lead trading program in the US is one example of emissions trading based on relative standards (see Svendsen 1998). In 1982, the US Environmental Protection Agency limited the lead content in gasoline to 1.1 gram per gallon and tightened the standard in following years to 0.1 gram in 1986. Refineries that remained below the standard could sell credits to other refineries. Another example is the Dutch NO_x emissions trading scheme that started on 1 June 2005 (Ministry of VROM 2004a,b). In this scheme, a distinction is made between combustion and process installations. The former emit NO_x as a result of the combustion of fuels. The standard for these installations is based on the amount of NO_x per gigajoule (GJ) of fuel used, decreasing from 68 gram/GJ in 2005 to 40 g/GJ in 2010. Hence, combustion installations face a relative input standard. Process installations however are regulated through a relative output standard determined as allowed NO_x emissions per unit of output that differs per process. Again, firms that remain below the standard are allowed to sell credits.

In the following, emissions trading based on a cap on emissions will be denoted by permit trading, while emissions trading based on relative output standards will be denoted as credit trading. It is very well possible for permit and credit trading to be combined, both at the national and at the international level. The UK greenhouse gas emissions trading scheme, started in 2002, already combines both systems (DETR 2001). In the Netherlands, a CO_2 emissions trading scheme was proposed where the energy-intensive exporting sectors were regulated though a credit trading scheme, while the remaining sectors were regulated through permit trading (CO2 Trading Commission 2002). The European Commission has chosen to apply a cap-and-trade system from January 2005, so that a combination of permit and credit trading for greenhouse gases should not be possible within the EU anymore. However, several countries and especially US states have expressed an interest to join the EU scheme. If these jurisdictions set up a domestic credit trading scheme, combined trading between them and the EU would occur.

The aim of this paper is to give an insight into the functioning of and the differences between permit and credit trading and into the implications of combing the two schemes. To this end, a partial equilibrium model of a polluting industry is developed. Two types of market structure are considered: perfect competition and Cournot oligopoly. In both cases, the number of firms is endogenous in the long run. To enable a comparison between the instruments, it is assumed throughout the paper that the government has imposed a ceiling on total industry emissions.

Credit trading is based on relative standards and therefore shares many characteristics with the latter instrument. This is especially the case when the industry is homogeneous since then there will be no trade in emissions. Ebert (1998, 1999) analyzes relative standards under perfect competition and Cournot oligopoly, but his analysis is limited to the short run where the number of firms is given.[1] In addition, Ebert (1998, 1999) assumes that a firm's cost function is additively separable in production and abatement cost. We will work with a more general cost function. Dijkstra (1999) analyzes relative and absolute standards, emission taxation and permit trading in the short run and in the long run, but only for perfect competition. The conclusions from this literature are that relative standards lead to higher industry output and higher marginal abatement costs than absolute emission ceilings and permit trading. Furthermore, Dijkstra (1999) shows that in the long run, production per firm is lower and the total number of firms is higher under relative standards than under permit trading.

Boom (2001) was the first to give credit trading some thought. His analysis shows that output will be larger under credit trading than under permit trading (see also Boom and Nentjes 2003). Fischer discusses several instruments, one of which is credit trading, under perfect (Fischer, 2001) and imperfect (Fischer 2003b) competition. She shows that credit trading can be seen as a tax on emissions equal to the credit price combined with a subsidy per unit of output equal to the average value of emissions embodied in output (credit price times the relative standard times output). Because of this, output under perfect competition will be larger than optimal. The socially optimal pollution level is achieved with a strict standard that results in a credit price above the Pigouvian tax rate. Fischer (2001, 2003b) assumes constant marginal production costs (decreasing in the emissions-to-output ratio). She only analyzes the short-run effects, given the number of firms. Fischer (2003b) assumes that with imperfect competition a firm realizes that when it increases its output, the government will tighten the relative standard. We will take this effect into account in the long run only.

Fischer (2003a) discusses the effect of combining permit and credit trading for two perfectly competitive sectors. She concludes that such a combination always leads to higher total emissions. However, this conclusion is based on the assumption that governments will not set a stricter relative standard in the credit sector.

The existing literature has already given some insight in the differences between permit and credit trading. This chapter adds to the existing literature in several ways. First, it gives a more formal analysis of the impacts of the two schemes and analyzes the long-run impacts on industry structure. Second, the paper gives a full analysis of the performance of the two schemes under

[1] Helfand (1991) analyzes several forms of standards, including relative standards, keeping the product price constant. However, different standards will typically result in different product prices.

imperfect competition. Different from other studies on environmental policy under imperfect competition, entry and exit is endogenous in our model. Modeling imperfect competition in this way leads to rather different results than when the number of firms is fixed. Furthermore, we analyze the effects of combining permit and credit trading formally, showing that this may both decrease or increase welfare.

Another issue often ignored is that the number of firms must be an integer. In our general model of perfect competition we will ignore this integer constraint as well. One might conjecture that this is rather harmless, because the number of firms is very large (Dijkstra 1999, p. 91, fn 14). In our simulation with a specific model, we will examine the consequences of the integer constraint. The integer constraint has particulary dramatic consequences under imperfect competition. We find that it may be impossible to implement certain levels of total industry emissions with permit or credit trading. It can also occur that there are multiple levels of the relative standard that achieve the same level of industry emissions.

The analysis consists of two parts. In the next section, we develop a partial equilibrium model. Here, both the short-run and long-run consequences of the two types of emissions trading are discussed and the effects on firm and total production, abatement costs, numbers of firms in the industry and welfare are given. Furthermore, an analysis of combined trading is given in section 2.4. However, some issues remain unresolved in the general model. Therefore, and to illustrate the properties of the two schemes, we run simulations with a more specific model in section 3. Finally, section 4 gives some conclusions.

2 A General Model

In this section, a general model of permit and credit trading is developed, which will be used to analyze the cases of perfect and imperfect competition. In all cases, it is assumed that the government wants to regulate an industry's emissions of a pollutant so that the total level does not exceed the limit L. The industry consists of $n > 1$ identical firms. Costs of production for a single firm are given by $C(q, E)$, where q gives the level of output and E the level of emissions. The properties of the cost function are $C_q > 0$, $C_{qq} \geq 0$, $C_{qE} \leq 0$, $C_E < 0$ and $C_{EE} \geq 0$. Inverse demand for the product is given by $p = p(Q)$, with $Q = \sum_{i=1}^{n} q_i$.

2.1 Perfect Competition

With perfect competition, the number of firms in the market is large and no single firm has an influence on the product or emissions quota price. In this section, we ignore the integer constraint on the number of firms. We will first analyze optimal firm behavior in the short run and then discuss the effects on the industry in the long run.

Short run. In the short run entry and exit do not take place. Therefore, the number of firms in the sector is given. Because of this, it is possible that firms will receive a profit, or incur losses in the short run.

With permit trading, each incumbent firm receives an initial amount of permits $\bar{E}$. The price of permits that arises in the market is denoted by R^p. The profit function of the firm is then given by

$$\pi = pq - C(q, E) - R^p(E - \bar{E})$$

The firm maximizes profits, which results in the following first order conditions

$$\frac{\partial \pi}{\partial q} = p - C_q = 0 \tag{1}$$

$$\frac{\partial \pi}{\partial E} = -C_E - R^p = 0 \tag{2}$$

The first condition says that marginal revenue, in this case price, should be equated with marginal costs of production. Since $C_{qE} < 0$, regulation results in an increase in production costs and therefore an increase in the product price. The profit-maximizing emission level is found by equating the marginal costs of emissions to the price of permits. Condition (2) ensures that marginal abatement costs are equalized between firms.

With credit trading, the scheme is based on a limit on emissions per unit of output. Let this relative standard be given by $\bar{e}$. Total allowed emissions for the firm is then $\bar{e}q$ plus or minus the number of credits bought or sold respectively. Under these conditions, profits for the firm are given by

$$\pi = pq - C(q, E) - R^c(E - \bar{e}q)$$

where R^c is the market price for credits. The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = p - C_q + R^c\bar{e} = 0 \tag{3}$$

$$\frac{\partial \pi}{\partial E} = -C_E - R^c = 0 \tag{4}$$

These can be combined to give

$$p = C_q + \bar{e}C_E \tag{5}$$

Since (4) holds for all firms, marginal abatement costs will be equalized between firms. Hence, credit trading achieves an efficient distribution of the abatement burden across firms. However, as a comparison between (3) and (1) shows, the production levels under the two schemes will not be identical. With credit trading, the term $R^c\bar{e}$ makes that firms no longer equate marginal production costs to the price of the product, but to a lower level, indicating that in equilibrium total output will be higher and the product price lower under credit trading. The additional factor can be seen as an output subsidy (Fischer (2001)) since the firm is allowed to emit more when it produces more.

It is now possible to determine the difference in impact of the two schemes in the short run:

Proposition 1 *Under perfect competition and in the short run, and with equal total emissions,* *credit trading will lead to higher total and firm output ($Q^c > Q^p$, $q^c > q^p$) and to a higher emission quota price ($R^c > R^p$) than permit trading.*

Proof: In the short run, $n^c = n^p = n$. Since $L^c = L^p = L$, we have that $E^c = E^p$. Furthermore, from (1) and (5) it follows that $Q^c > Q^p$. This combined with $n^c = n^p = n$ gives $q^c > q^p$. The fact that $q^c > q^p$ combined with $E^c = E^p$ gives $R^c > R^p$ since $C_{Eq} < 0$. $\square$

Long Run In the long run, the number of firms is variable. Firms remaining in the industry have zero profits in equilibrium.

For permit trading, this implies that the long-run equilibrium conditions are

$$p = C_q \tag{6}$$

$$pq = C(q, E) + R^p E \tag{7}$$

$$-C_E = R^p \tag{8}$$

$$nE = L \tag{9}$$

Note that the permits $\bar{E}$ grandfathered to the firms do not appear in the zero-profit condition (7). The reason is that the permits represent an opportunity cost to the firm. If the firm does not cover its opportunity costs of emission, it would be better off if it sold its permits and closed production.

The long-run conditions for credit trading are

$$p = C_q + \bar{e}C_E \tag{10}$$

$$pq = C(q, E) \tag{11}$$

$$-C_E = R^c \tag{12}$$

$$nE = L \tag{13}$$

Contrary to the permit trading scheme, a firm that stops producing does not receive any credits and can therefore not sell them to other firms remaining in the industry. Thus under credit trading, a firm only needs to cover its operating cost $C(q, E)$ (equation (11)). Condition (13) together with the assumption that firms are identical implies that $E = \bar{e}q$. As a final condition for both schemes, the inverse demand function is given by

$$p = p(nq) \tag{14}$$

We can now show the following:

Proposition 2 *Under perfect competition and in the long run with equal industry emissions, credit trading leads to higher industry output ($Q^c > Q^p$), a higher emission quota price ($R^c > R^p$), lower firm output ($q^c < q^p$), lower firm emissions ($E^c < E^p$) and a larger number of firms in the industry ($n^c > n^p$) than under permit trading.*

Proof: For permit as well as credit trading, we find from (6) and (7), and (10) and (11) respectively, that production is determined by

$$C(q,E) = qC_q - RE \tag{15}$$

Suppose that $p^c > p^p$. Then

$$n^c q^c < n^p q^p \Leftrightarrow \frac{n^c q^c}{n^c E^c} < \frac{n^p q^p}{n^p E^p} \Rightarrow \frac{E^c}{q^c} > \frac{E^p}{q^p} \tag{16}$$

From (15) it follows that (q, E) follows the same path for the two schemes, but at a different speed. Furthermore, E/q must decline as L declines from a non-binding level to zero. So from (16) it follows that (E^p, q^p) is ahead of (E^c, q^c). Then from $dE/dL, dq/dL > 0$ (see appendix A) it follows that $E^c > E^p$ and $q^c > q^p$. Furthermore, we find

$$\frac{C(q^c, E^c)}{q^c} < \frac{C(q^p, E^p)}{q^p} \quad \text{since} \quad p^c = \frac{C(q^c, E^c)}{q^c} \quad \text{and} \quad \frac{dp}{dL} < 0$$

But we had assumed

$$\frac{C(q^c, E^c)}{q^c} = p^c > p^p > \frac{C(q^p, E^p)}{q^p}$$

This shows that $p^c > p^p$ is impossible, so that we must have $p^c < p^p$.

This shows that $Q^c > Q^p$. It then follows that

$$\frac{L}{Q^c} < \frac{L}{Q^p} \quad \Leftrightarrow \quad \frac{n^c E^c}{n^c q^c} < \frac{n^p E^p}{n^p q^p} \quad \Leftrightarrow \quad \frac{E^c}{q^c} < \frac{E^p}{q^p} \tag{17}$$

Equation (15) implies that if $R^c = R^p$, output and emissions and hence E/q per firm are identical under the two schemes. Then from (17) and $dR/dL > 0$, it follows that $R^c > R^p$. From this and (15) it then follows that $E^c < E^p$ and $q^c < q^p$. Furthermore, from $Q^c > Q^p$ and $q^c < q^p$ it follows that $n^c > n^p$. $\square$

This shows that the long-run effects are rather different from the short-run effects. In the short run, output per firm is higher under credit trading than under permit trading, while emissions per firm are equal under the two schemes. In the long run, both output and emissions per firm are lower under credit trading than under permit trading. On the other hand, an important similarity between the short and long run is that abatement costs per unit of output are higher under credit trading than under permit trading.

In appendix A, the effect of a change in the total emissions limit L on product price, output, emissions per firm and the number of firms is derived. For both permit and credit trading we find $dq/dL > 0$, $dE/dL > 0$ and $dp/dL \leq 0$. The introduction of emissions trading, starting from a position without emission control policy, will result in a decrease in production per firm, a decrease in emissions per firm and an increase in the price of the product. The latter also implies that total output will be lower. For both schemes, it remains unclear whether the number of firms increases or decreases as a result of regulation. The outcome depends on the cost function and on the slope of the demand function. We shall explore this issue in more detail in our simulations in Section 3.

2.2 Imperfect Competition

With imperfect competition, each firm has an influence on the market price of the product. We will assume Cournot competition between the firms. The emission trading scheme is confined to the sector analyzed, which implies that firms should also have market power on the emissions quota market. In such a market, firms will bargain with each other over the price. The outcome is dependent on the market power of the individual firms and the initial distribution of emission quotas over the participants in the quota market. A complicating factor is that incumbent firms may form a cartel, refusing to sell emission quotas to new entrants, thereby effectively deterring entry if emissions are necessary for production. The existence of an effective competition authority could prevent such behavior, however. In order not to complicate the analysis more than necessary and to keep focus on the main issue of the paper, it is assumed that firms cannot effectively deter entry. Furthermore, it is assumed that the outcome of bargaining between firms is the perfectly competitive emission quota price.

Short run. With imperfect competition and permit trading, the profit function for a firm is:

$$\pi = p(Q)q - C(q,E) - R^p(E - \bar{E})$$

The first order conditions for profit maximization are:

$$\frac{\partial \pi}{\partial q} = p'q + p - C_q = 0 \tag{18}$$

$$\frac{\partial \pi}{\partial E} = -C_E - R^p = 0 \tag{19}$$

These conditions imply that the firm equates marginal revenue with marginal production costs and marginal costs of abatement with the price of permits.

We would like to ensure that the equilibrium is stable. To this end, we determine the slope of the reaction curve by total differentiation of (18) and rearranging:

$$-1 < \frac{dq_i}{dQ_{-i}} = -\frac{qp'' + p'}{qp'' + 2p' - C_{qq}} < 0 \tag{20}$$

where $Q_{-i} = \sum_{j=1,j\neq i}^{n} q_j$. The denominator is negative by the second order condition (see appendix B), and so we need the numerator to be negative as well to assure that the Nash equilibrium is stable. In the following we shall assume that this is the case. In fact, we shall assume that the stricter condition:

$$nqp'' + 2p' < 0 \tag{21}$$

is satisfied. This also guarantees that the denominator on the RHS of (20) is negative.

When regulation takes the form of credit trading, the profit function becomes

$$\pi = p(Q)q - C(q, E) - R^c(E - \bar{e}q)$$

The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = p'q + p - C_q + R^c\bar{e} = 0 \quad (22)$$

$$\frac{\partial \pi}{\partial E} = -C_E - R^c = 0 \quad (23)$$

It is clear that the short-run first order conditions for imperfect competition closely resemble those for perfect competition. The only difference is that under imperfect competition firms take the effect of changes in their own output on the price of the product into account.

For credit trading, the slope of the reaction function is found from (22):

$$-1 < \frac{dq_i}{dQ_{-i}} = -\frac{qp'' + p'}{qp'' + 2p' - C_{qq} - \bar{e}C_{Eq}} < 0$$

The nominator is negative by (21) and the denominator is negative by the second order condition (see appendix B).

The relative impact of the two schemes in the short run is given by

Proposition 3 *Under imperfect competition and in the short run, credit trading will lead higher total and firm output ($Q^c > Q^p$, $q^c > q^p$) and to a higher emission quota price ($R^c > R^p$) than under permit trading. Firm emissions are identical under the two schemes ($E^c = E^p$).*

Proof: See Proof of Proposition 1.□

Hence, the short-run effects of the two schemes under imperfect competition are basically the same as under perfect competition.

Long Run. In the long run the number of firms can vary through entry and exit. More precisely, the equilibrium number of firms will be such that if one more firm entered the market, all firms would make a loss. That is, n^* is the equilibrium number of firms with:

$$\pi(n^*) \geq 0, \quad \text{and} \quad \pi(n^* + 1) < 0 \quad (24)$$

With permit trading, the long run profit function becomes:

$$\pi = p(Q)q - C(q, E) - R^pE \quad (25)$$

The long-run conditions for permit trading with imperfect competition are then:

$$
\begin{aligned}
p'q + p &= C_q \\
-C_E &= R^p \\
nE &= L
\end{aligned}
$$

and (24). The resulting equilibrium is stable as the slope of the reaction function is still given by (20).

With credit trading, the firm knows that its actions will have an influence on the standard set. Specifically, when a firm increases its output, total industry output increases and therefore the government will set a stricter standard in order to keep industry emissions constant. Recall from above that the standard is $\bar{e} = \frac{L}{Q}$. The profit function with credit trading can then be rewritten as:

$$\pi = p(Q)q - C(q, E) - R^c \left(E - \frac{L}{Q} q \right)$$

The long-run conditions for profit maximization then become:

$$
\begin{aligned}
p'q + p &= C_q - R^c \left(\frac{n-1}{n} \frac{E}{q} \right) \\
-C_E &= R^c \\
nE &= L
\end{aligned}
\tag{26}
$$

and (24). From a comparison of (26) with (22), it is clear that in the long run, firms have less incentive to expand production since they know that an increase in output will lead to a tightening of the relative standard. With monopoly $Q = q$, and (26) becomes $p'q + p = C_q$. The monopolist completely internalizes the tightening of the standard following an increase in output. In this case, there is no difference between a credit and a permit trading scheme. More generally: with an equal number of firms under both types of regulation, the lower the number of firms in the market, the more closely the outcomes under credit and permit trading resemble each other.

Compared with the short run, the firm no longer takes the relative standard as given. Therefore, the slope of the reaction function, found from (26), is now given by:

$$-1 < \frac{dq_i}{dQ_{-i}} = -\frac{nq(qp'' + p') + C_E \left(\frac{n-1}{n}\right) \frac{E}{q}}{nq(qp'' + 2p' - C_{qq}) + C_E \left(\frac{n-1}{n}\right) \frac{E}{q}} < 0$$

The denominator and numerator are negative by (21), so that the Nash equilibrium is stable.

For the relative impact of the two schemes in the long run we find:

Proposition 4 *In the long run under imperfect competition, the number of firms under credit trading will be equal or larger than under permit trading ($n^c \geq n^p$). Then,*

1. *If $n^c = n^p$, credit trading will lead to higher total and firm output ($Q^c > Q^p$, $q^c > q^p$) identical firm emissions ($E^c = E^p$) and to a higher emission quota price ($R^c > R^p$) than under permit trading.*

2. *If $n^c > n^p$, credit trading leads to higher total output ($Q^c > Q^p$) and lower firm emissions ($E^c < E^p$).*

Proof: Assume that $n^c = n^p$. From the profit functions and (18) and (22) it then follows that under both permit and credit trading profits can be written as

$$\pi = qC_q + EC_E - p'q^2 - C(q, E)$$

Differentiating partially with respect to q yields:

$$\frac{\partial \pi}{\partial q} = qC_{qq} + EC_{qE} - q(2p' + nqp'') > 0$$

The inequality follows from (21) and (60). Since $q^c > q^p$ from (18) and (26) when $n^c = n^p$, it also follows that $\pi^c > \pi^p$ when $n^c = n^p$. This shows that there is a greater possibility for entry under credit trading than under permit trading and hence, that $n^c \geq n^p$. In Part 1), since $n^c = n^p$ and $L^c = L^p$, it follows that $E^c = E^p$. Furthermore, as we have seen above, it is clear that $Q^c > Q^p$. This combined with $n^c = n^p$ gives $q^c > q^p$. The fact that $q^c > q^p$ combined with $E^c = E^p$ gives $R^c > R^p$ since $C_{Eq} < 0$. In Part 2), $Q^c > Q^p$ follows from $dp/dn < 0$ (see appendix B). $E^c < E^p$ follows immediately from $n^c > n^p$ and $L^c = L^p$. □

Unfortunately, it is not possible to determine the relationship between q^c and q^p and that between R^c and R^p for $n^c > n^p$. As is clear from the analysis in appendix B, for both schemes, q decreases as the number of firms increases. However it is not clear whether q^c is larger or smaller than q^p. For the emission quota price, the result of an increase in the number of firms is ambiguous. Therefore, we cannot say whether the credit price will be larger or smaller than the permit price.

For a fixed number of firms, we can determine what the effect of a change in L is on most other variables and thereby the effect of introducing regulation. In appendix B, it is shown that $dq/dE > 0$, $dp/dE < 0$ for both schemes, and $dR^p/dE^p < 0$ for permit trading. For credit trading, the expression for dR^c/dE^c is ambiguous. However, when regulation goes from non-binding to binding, $dR^c/dE^c < 0$. Thus, the introduction of emission trading, starting from a position without regulation, will always lead to lower firm and total output and to higher marginal abatement costs. When entry or exit takes place we cannot analyze the effect of a change in L because the number of firms changes discretely which will have a large effect on the other variables.

We have assumed in this paper that the goal of environmental policy is to achieve a certain level of industry emissions L, lower than the unconstrained emission level. The question is

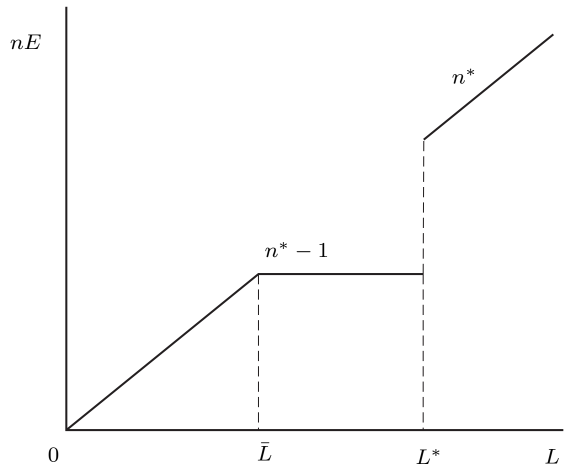

Figure 1: Some L not obtainable with PT

however, whether environmental policy always can achieve the emission limit set.

Proposition 5 *In a permit trading scheme, when the number of firms n^P is increasing in the amount L of permits issued, it may be impossible to achieve certain levels of total industry emissions.*

Figure 1 which shows the relation between the total amount L of permits issued and industry emissions nE, illustrates this Proposition. For $L \geq L^*$, there are n^* firms in the industry and emissions are equal to the limit: $n^*E = L$. However, profits are decreasing as the government issues less and less permits. For $L < L^*$, only $n^* - 1$ firms can survive in the industry. As long as $L \geq \bar{L}$, these $n^* - 1$ firms can emit as much as they like without exceeding the total limit for the industry. This is because the firms only want to emit $\bar{L}$ between them. There will be an excess supply of permits, so that the permit price is zero. As a result, industry emission levels between $\bar{L}$ and L^* cannot be attained. We will see an example of this in Section 3.2, Table 10.

Proposition 6 *In a credit trading scheme*

i) If n^c is increasing in $\bar{e}$, some L cannot be realized.

ii) If n^c is decreasing in $\bar{e}$, some L can be realized with more than one $\bar{e}$.

Proof: i) If $\bar{e}$ remains the same, and n^c decreases, it is shown in appendix B that total output decreases as well. Since $\sum_{i=1}^{n} E_i = \bar{e}Q$, it follows that total emissions also decrease discretely. It then follows that certain L cannot be realized. ii) If at fixed $\bar{e}$ the number of firms increases, total output increases (see appendix B) and thereby total emissions. Hence, at the $\bar{e}$ where n^c increases, total emissions increase, whereafter they decrease as $\bar{e}$ decreases. It then follows that certain L can be obtained with different $\bar{e}$ and n^c.□

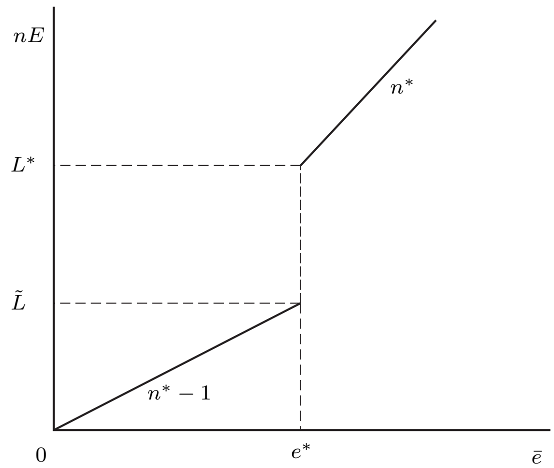

Figure 2: Some L not obtainable with CT

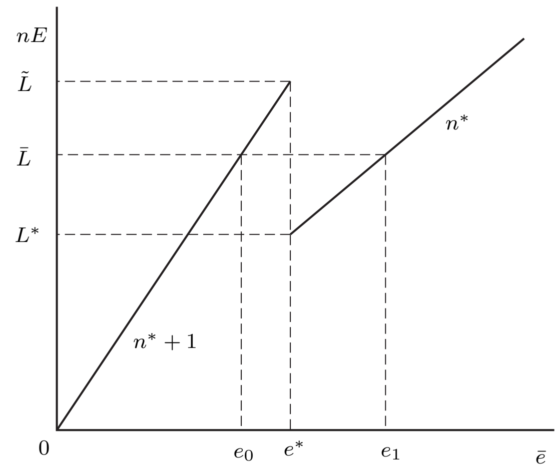

Figure 3: Some L obtainable with different $\bar{e}$

Figure 2 illustrates the case where the government cannot reach certain L under credit trading. For $\bar{e} > e^*$, there are n^* firms in the industry. However, profits decrease as the relative standard is tightened. When $\bar{e} < e^*$, there is only room for $n^* - 1$ firms in the industry. As the number of firms drops at e^*, so do total emissions: from $L^* \equiv e^* n^*$ to $\tilde{L} \equiv e^*(n^* - 1)$ in Figure 2. Industry emission levels between $\tilde{L}$ and L^* cannot be achieved with credit trading. An example of this is given in Table 11 of Section 3.2.

Figure 3 illustrates the case where the same level of industry emissions can be achieved with different levels of the relative standard. For $\bar{e} > e^*$, there are n^* firms in the industry. Now profits increase as the relative standard is tightened. When $\bar{e} < e^*$, there is room for $n^* + 1$ firms in the industry. As the number of firms rises e^*, so do total emissions: from $L^* \equiv e^* n^*$ to $\tilde{L} \equiv e^*(n^* + 1)$ in Figure 3. This implies that any industry emission level between $\tilde{L}$ and L^* can be achieved with two levels of the relative standard. Total emissions $\bar{L}$, for instance, can be achieved with a relative standard of e_0, resulting in $n^* + 1$ firms in the industry (where $e_0 = \bar{L}/[n^* + 1]$) and with a relative standard of e_1, resulting in n^* firms (where $e_1 = \bar{L}/n^*$). To maximize welfare, the government should choose the stricter relative standard e_0. This standard leads to the highest number of firms, which increases total output and diminishes market power. Table 13 in Section 3.2 provides an example of this.

2.3 Welfare

The emission trading schemes described above will have different impacts on welfare. To compare the performance of the two instruments, we assume that they are set such as to give the same amount of total emissions L. Here, welfare is given by consumer plus producer surplus. This is given by the area under the demand function minus production costs. The problem now is to maximize:

$$W = \int_0^{nq} p(Y)dY - nC(q,E) - \lambda(nE - L) \tag{27}$$

In the short run, only production is variable, while the number of firms n and the total ceiling on emissions L are fixed. The latter two imply that E and λ are fixed. Maximizing (27) with respect to q gives as the short run first order condition:

$$p = C_q \tag{28}$$

In the long-run, all variables can change. Therefore, to find the optimum, we must maximize (27) with respect to q, n, E, and λ, which gives:

$$\begin{aligned} p &= C_q \\ pq &= C(q,E) + C_E E \end{aligned} \tag{29}$$

This enables us to state the following for perfect competition:

Proposition 7 *Under perfect competition, only permit trading leads to optimal welfare, while credit trading leads to lower short-run and long-run welfare.*

Proof: Comparing (28) with (1) (5) for the short run, and (29) with (6)-(9) and (10)-(13) for the long run, it follows immediately that permit trading fulfills all optimality conditions for welfare while credit trading does not. □

This result may seem somewhat odd since credit trading leads to higher output and thereby to a larger consumer surplus. Since profits are zero under both instruments, one might derive from this that credit trading would lead to higher welfare. There are however two other effects that have to be taken into account. First, costs of production are higher under credit trading. Credit trading is an inefficient instrument because it limits the options for reducing emissions. One effective way to reduce emissions is by reducing output. However, under credit trading, this option will not be utilized to its maximum because reducing output also reduces the total allowable amount of emissions for the firm. Second, under permit trading, the firm has to cover the opportunity cost of its emissions, which is not the case under credit trading. This is a cost to the firm, but it is a resource rent reaped by the shareholders. Under credit trading, the resource rent is competed away.

With imperfect competition, it is not immediately clear which instrument leads to highest welfare. There are three effects that have to be taken into account. In general, imperfect competition leads to lower than optimal production. As we have seen above, credit trading leads to higher output than permit trading and therefore seems to have an advantage. Credit trading also results in more (at least not less) firms in the sector. This means that under credit trading firms have less market power, which again leads to a higher output level than under permit trading. However, credit trading also leads to higher abatement costs than permit trading. The overall effect depends on the size of the three effects.

2.4 Combining Permit and Credit Trading

When permit and credit trading are combined, emission quotas will flow from the sector with the lowest to the sector with the highest quota price. For simplicity, we will focus on the case where two sectors are identical in every respect, except that they operate on two different markets (with identical demand functions) and that one sector is regulated through permit trading while the other is regulated through credit trading. As was shown above, under perfect competition and under imperfect competition with $n^c = n^p$, the credit price is always higher than the permit price so that permits will flow to the credit sector. However, with imperfect competition and $n^c > n^p$, this need not be the case so that here credits may flow to the permit sector.

Irrespective of the direction in which credits flow, the effect of combining the two systems is that the sector selling emission quotas will reduce production and the product price will increase. The buying sector will expand production and the product price in this sector will fall. Thus combined trading stimulates output of the sector which initially had the highest emission quota price at the expense of output in the other sector.

Proposition 8 *Assume two perfectly competitive industries that are identical in every respect, except that they produce different products. One industry is regulated through permit trading and the other through credit trading. Allowing emissions trading between the two sectors will lead to an identical emissions quota price ($R^c = R^p = R$), the permit sector selling quotas to the credit sector, and*

1. *in the short run, to a decrease in output per firm and an increase in product price in the permit sector. In the credit sector, firm output will increase and product price will decrease. Furthermore, it will lead to higher firm emissions and output ($E^c > E^p$ and $q^c > q^p$) and lower product price ($p^c < p^p$) in the credit sector than in the permit sector.*

2. *in the long run to a decrease in output and emissions per firm and an increase in the product price in the permit sector. In the credit sector, the product price will decrease, while firm emissions and output may increase or decrease. In both sectors, the number of firms may increase or decrease. Furthermore, combined trading will lead to identical firm emissions ($E^c = E^p$), identical firm output ($q^c = q^p$), a higher number of firms ($n^c > n^p$), and a lower product price ($p^c < p^p$) in the credit sector than in the permit sector.*

Proof. Combining the two schemes will give $R^c = R^p = R$ since the quota market is perfectly competitive. Since $R^c > R^p$ in the short run (Proposition 1) as well as in the long run (Proposition 2), the quota price will decrease for the credit sector and increase for the permit sector. As a result, the permit sector sells quotas to the credit sector. Then

1. In the short run, combining the schemes leads to a decrease in E^p and an increase in E^c. In appendix A, it is shown that $dq^p/dE^p > 0$, $dp^p/dE^p < 0$, $dq^c/dE^c > 0$ and $dp^c/dE^c < 0$.

Thus, combined trading results in a decrease in q^p and p^c and an increase in p^p and q^c. Since separate schemes already feature $q^c > q^p$ and $p^c < p^p$, the same inequalities hold for combined trading.

2. In the long run, combining the schemes leads to a decrease in L^p and an increase in L^c. In appendix A, it is shown that $dq^p/dL > 0$, $dE^p/dL > 0$, $dp^p/dL < 0$ and $dp^c/dL < 0$ while the signs of dn^p/dL, dq^c/dL, dE^c/dL and dn^c/dL are ambiguous. From (15) it follows that q and E follow the same path with permit and credit trading. Combined with $R^c = R^p = R$, this means that $E^c = E^P$ and $q^c = q^P$. From (6) and (10) we find that $p^c < p^p$. Combining this with $q^c = q^p$, it is clear that $n^c > n^p$ must hold. □

With imperfect competition and $n^c > n^p$, we could not state whether the credit price was higher or lower than the permit price. Therefore we can only state a result for the case where $n^c = n^p$:

Proposition 9 *Assume two imperfectly competitive industries that are identical in every respect, except that they produce different products. One industry is regulated through permit trading and the other through credit trading. Assume furthermore that the outcome in the emissions quota market is the perfectly competitive quota price so that $R^c = R^p = R$. Then, under combined trading, in the short run and in the long run with $n^c = n^p$, the permit sector sells quotas to the credit sector, resulting in $E^c > E^p$. In the permit sector firm output will decrease and product price will decrease, while in the credit sector, firm output will increase and product price will decrease. Furthermore, we find that $E^c > E^p$, $q^c > q^p$ and $p^c < p^p$.*

Proof: With $n^c = n^p$ under separate schemes, $R^c > R^P$ (Propositions 3 and 4). Combined trading then leads to an increase in E^c and a decrease in E^p. As is shown in appendix B, for both the short and long run, $dq/dE > 0$ and $dp/dE < 0$ for both schemes. Since with separate schemes we had $q^c > q^p$ and $p^c < p^p$, the result follows immediately. □

2.4.1 Welfare

It follows directly from Proposition 7 that a system where one sector is regulated through permit trading and the other through credit trading is not welfare maximizing. However, this does not immediately show what happens to welfare when a permit and credit sector are allowed to trade. This is shown formally below, both for the short and the long run for perfect competition and for the case where $n^c = n^p$ under imperfect competition.

The effect of combining the two schemes on total welfare can be analyzed by determining the change in welfare as a result of a change in the division of the emission ceiling over the two sectors. Welfare is given by:

$$W = \int_0^{Q^c} p^c(Q^c)dQ^c - n^cC^c(q^c, E^c) + \int_0^{Q^p} p^p(Q^p)dQ^p - n^pC^p(q^p, E^p)$$

with the total emission limit given by:

$$n^c E^c + n^p E^p = L^c + L^p = S \tag{30}$$

In the short run, the number of firms is fixed, so we find:

$$\frac{dE^p}{dE^c} = -\frac{n^c}{n^p} \tag{31}$$

We know from Propositions 8 and 9 that combined trading leads to an increase in E^c. Differentiating welfare with respect to E^c, while holding n^c and n^p constant, and using (31) gives for the short run:

$$\frac{dW}{dE^c} = n^c p^c \frac{dq^c}{dE^c} - n^c C_{q^c} \frac{dq^c}{dE^c} - n^c C_{E^c} - n^c p^p \frac{dq^p}{dE^p} + n^c C_{q^p} \frac{dq^p}{dE^p} + n^c C_{E^p} \tag{32}$$

In the long run, the number of firms can change, and from (30) we find that $dL^p/dL^c = -1$. The change in welfare is then given by:

$$\begin{aligned} \frac{dW}{dL^c} = {} & q^c p^c \frac{dn^c}{dL^c} + n^c p^c \frac{dq^c}{dL^c} - C^c(q^c, E^c) \frac{dn^c}{dL^c} - n^c C_{q^c} \frac{dq^c}{dL^c} - n^c C_{E^c} \frac{dE^c}{dL^c} \\ & - q^p p^p \frac{dn^p}{dL^p} - n^p p^p \frac{dq^p}{dL^p} + C^p(q^p, E^p) \frac{dn^p}{dL^p} + n^p C_{q^p} \frac{dq^p}{dL^p} + n^p C_{E^p} \frac{dE^p}{dL^p} \end{aligned} \tag{33}$$

Perfect Competition For the short run, (32) can be simplified by using (1) and (5) to:

$$\frac{dW}{dE^c} = n^c \left([C_{E^p} - C_{E^c}] + C_{E^c} \frac{E^c}{q^c} \frac{dq^c}{dE^c} \right) \tag{34}$$

For the long run, (33) can be rewritten using (6), (7), (10) and (11) and noting that $E^c = \bar{e} q^c$ and $E\frac{dn}{dL} + n\frac{dE}{dL} = 1$ for both sectors. We find:

$$\frac{dW}{dL^c} = \left[C_{E^p} - n^c C_{E^c} \frac{dE^c}{dL^c} \right] + n^c C_{E^c} \frac{E^c}{q^c} \frac{dq^c}{dL^c} \tag{35}$$

There are two effects. First, abatement costs increase in the permit sector and decrease in the credit sector (the term between square brackets on the RHS of (34) and (35)). Since initially marginal abatement costs are higher in the credit sector, this leads to a welfare increase. Secondly, production increases in the credit sector and decreases in the permit sector. In itself, the production change in the permit sector is not distortionary, because output is optimal, given total emissions. In the credit sector, however, output is larger than optimal, and the gap between actual and optimal output increases when the two sectors are combined. This effect is given by the second term on the RHS of (34) and (35) and causes a decrease in welfare. The total effect on welfare then depends on the size of these two effects. If marginal abatement costs are much higher in the credit sector, while the output effect is not very large, combining the two schemes will lead to an increase in welfare.

Imperfect Competition Using (18), (22) and (23), (32) can be rewritten to find:

$$\frac{dW}{dE^c} = n^c \left([C_{E^p} - C_{E^c}] + p^{p\prime} q^p \frac{dq^p}{dE^p} + [p^c - C_{q^c}] \frac{dq^c}{dE^c} \right)$$

Again there are two effects. The first effect is the same as with perfect competition. Abatement costs increase in the permit sector and decrease in the credit sector as a result of the transfer of permits to the credit sector. The second effect is the output effect. Production in the credit sector increases, while it decreases in the permit sector. This leads to a loss in the permit sector equal to $n^c p^{p\prime} q^p \frac{dq^p}{dE^p}$. In the credit sector, the effect is depends on whether output is above or below the welfare optimum given by $p = C_q$. Hence under imperfect competition, an increase in welfare is more likely when the distortionary effect of credit trading is small and $p^{c\prime} < p^{p\prime}$ and $\frac{dq^c}{dE^c} > \frac{dq^p}{dE^p}$. That is, combining the two schemes is more likely to lead to an increase in welfare when the inverse demand function is concave and output in the credit sector increases more than it decreases in the permit sector.

For imperfect competition, we cannot show the long-run effect of combining the two schemes on welfare when $n^c > n^p$. The problem is that it is hard to determine when entry or exit will take place and a change in the number of firms will have a large impact on the results.

3 Simulation

The analysis above leaves many questions open. Under perfect competition, the effects of combined trading on the number of firms and welfare are still not fully clear. Moreover, the size of the effects discussed above is unknown. Recall also that in the analysis above we ignored the constraint that the number of firms under perfect competition is an integer Furthermore, the outcome under imperfect competition is not entirely clear, especially in the long run when $n^c > n^p$. To analyze these problems, we will deploy a more specific model. Numerical simulations will then be used to generate several scenarios.

For the simulation, we will use the following cost function:

$$C(q, E) = aq^2 + b(q - E)^2 + K \qquad a, b, K > 0 \tag{36}$$

Here, a and b are parameters and K gives fixed costs. It can easily be verified that this cost function satisfies all first and second order conditions stated in this paper for the general function. Furthermore, the inverse demand function is linear and is given by

$$p(nq) = \alpha - \beta nq \qquad \alpha, \beta > 0 \tag{37}$$

The solutions of the simulation model are given in appendix C.

3.1 Perfect Competition

The general analysis in Section 2 already provided a thorough insight into the workings of the two schemes under perfect competition. The only question unanswered in that part was how the number of firms in the sector changes as it becomes regulated. We will therefore analyze this long run effect here in some detail. Furthermore, we will discuss the effect of a change in emission reduction targets, marginal abatement costs and demand function on the regulated sector.

The simulation results for perfect competition are given in Tables 1 to 6. All examples are constructed such that without regulation, firm output and emissions are 1, the number of firms is 100 and product price is 2. In Tables 1 to 3 the effect of a change in b in the cost function (36) is given for an emissions reduction level of 30%. In Tables 4 to 6, b is kept constant at 1, but the emission reduction level is varied between 10 and 100%. For each case, change in b or in L, there are three subcases. The three subcases differ from each other in that the demand function becomes more elastic.

In the model used for the simulations the number of firms is an integer. This differs from the model used in Section 2.1 where the number of firms does not have to be an integer and typically is not. This has several implications for the results. The main difference with the general model is that in the simulations, long-run profits may be positive. Firms will then not produce in their lowest average cost position, but at a larger output level. The results from Section 2.1 may now no longer hold. The simulations provide several examples of these deviations from the theory given in Section 2.1. In the following, we will first discuss the results for the separate schemes and after that those for combined trading.

In general, the simulation results confirm the results of the general analysis given in Section 2.1. Any deviations are due to the integer constraint on the number of firms. Regulation leads to lower industry output and higher product prices. In most cases production per firm is higher under permit than under credit trading, but total production and the number of firms are higher under credit trading. The Tables also show that in general, the credit price is higher than the permit price. Note however that there are some irregularities in Table 4. For emission reductions of 10, 20 and 90% the firm output level is *higher* under credit trading than under permit trading, while the theoretical analysis showed that the reverse should be the case. Notice however also that the number of firms is the same under both schemes. As we showed earlier, with an equal number of firms, firm output must be higher under credit trading than under permit trading. Furthermore, for emission reductions of 60, 70 and 80% the credit price is *lower* than the permit price.

As mentioned, a question still left open by the general analysis is the effect of regulation on the number of firms. As is shown in Appendix A, the number of firms may increase or decrease as a result of regulation, although credit trading always leads to a higher number of firms than permit trading. A review of Tables 1 through 6 shows that the number of firms in the market depends on the slope of the inverse demand function, and thereby the elasticity of demand,

Table 1: Perfect Competition: Inelastic Demand 1

$a = 1,\ K = 1,\ \alpha = 102,\ \beta = 1,\ q^0 = 1,\ n^0 = 100,\ E^0 = 1,\ p^0 = 2,\ L = 70$										
	Permit Trading					Credit Trading				
b	q^p	n^p	E^p	p^p	R^p	q^c	n^c	E^c	p^c	R^c
1	0.966	103	0.680	2.505	0.573	0.961	104	0.673	2.093	0.575
2	0.926	107	0.654	2.938	1.086	0.924	108	0.648	2.179	1.104
3	0.897	110	0.636	3.356	1.562	0.891	112	0.625	2.256	1.593
4	0.870	113	0.620	3.740	2.001	0.859	116	0.603	2.328	2.046
5	0.844	116	0.603	4.094	2.406	0.837	119	0.588	2.412	2.486
6	0.827	118	0.593	4.455	2.801	0.809	123	0.569	2.473	2.881
7	0.804	121	0.579	4.759	3.152	0.789	126	0.556	2.548	3.272
8	0.788	123	0.569	5.078	3.502	0.770	129	0.543	2.618	3.644
9	0.773	125	0.560	5.379	3.833	0.752	132	0.530	2.685	3.998
10	0.759	127	0.551	5.664	4.147	0.735	135	0.519	2.748	4.334

Combined Trading

	Permit Sector					Credit Sector			
b	q^p	n^p	E^p	p^p	R	q^c	n^c	E^c	p^c
1	0.966	103	0.679	2.506	0.574	0.961	104	0.674	2.093
2	0.926	107	0.652	2.947	1.095	0.924	108	0.651	2.176
3	0.897	110	0.634	3.371	1.578	0.891	112	0.628	2.252
4	0.869	113	0.616	3.767	2.029	0.867	115	0.613	2.337
5	0.844	116	0.599	4.135	2.447	0.844	118	0.599	2.415
6	0.820	119	0.583	4.479	2.840	0.816	122	0.579	2.474
7	0.797	122	0.567	4.804	3.211	0.796	125	0.566	2.542
8	0.781	124	0.558	5.134	3.572	0.777	128	0.553	2.609
9	0.760	127	0.543	5.433	3.912	0.764	130	0.547	2.683
10	0.746	129	0.534	5.731	4.239	0.746	133	0.534	2.742

Welfare

	Separate Schemes			Combined trading		
b	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
1	4991	4991	9983	4991	4991	9983
2	4983	4983	9966	4983	4983	9966
3	4976	4975	9950	4975	4975	9950
4	4968	4967	9936	4967	4968	9936
5	4961	4960	9921	4960	4962	9922
6	4955	4953	9908	4953	4955	9908
7	4949	4946	9895	4946	4949	9895
8	4943	4939	9882	4940	4942	9882
9	4937	4933	9870	4933	4937	9870
10	4931	4927	9858	4927	4931	9858

and on the marginal costs of abatement. In the cases given in Tables 1 and 4, the slope of the demand function is -1 and the elasticity of demand without regulation is -0.02. Under both permit and credit trading, the number of firms increases as compared with no regulation, although more so with credit trading than with permit trading. However, as the slope of the inverse demand function becomes flatter and demand more elastic, the number of firms in both sectors decreases as is clear from Tables 2 and 5 where the elasticity is -0.2 and Tables 3 and 6 where the elasticity is -2 under no regulation. The explanation for this is as follows. Regulation increases the cost of production and thereby the price of the product. If demand is inelastic, total output will not change much, while output will decrease by a large amount if demand is elastic. At the same time, regulation decreases the optimal production level for the firm and more so with credit trading than with permit trading. Then, when emissions are regulated, total output does not decrease much with inelastic demand, while output per firm does decrease, so

Table 2: Perfect Competition: Inelastic Demand 2

	$a = 1$, $K = 1$, $\alpha = 12$, $\beta = 0.1$, $q^0 = 1$, $n^0 = 100$, $E^0 = 1$, $p^0 = 2$, $L = 70$									
	Permit Trading					Credit Trading				
b	q^p	n^p	E^p	p^p	R^p	q^c	n^c	E^c	p^c	R^c
1	0.973	98	0.714	2.464	0.518	0.962	103	0.680	2.090	0.565
2	0.948	97	0.722	2.803	0.906	0.928	106	0.660	2.164	1.070
3	0.938	95	0.737	3.086	1.209	0.904	108	0.648	2.241	1.533
4	0.934	93	0.753	3.316	1.449	0.875	111	0.631	2.293	1.951
5	0.933	91	0.769	3.507	1.641	0.854	113	0.620	2.351	2.344
6	0.936	89	0.787	3.668	1.796	0.835	115	0.609	2.403	2.710
7	0.933	88	0.796	3.790	1.924	0.822	116	0.603	2.461	3.065
8	0.941	86	0.814	3.910	2.028	0.805	118	0.593	2.501	3.388
9	0.941	85	0.824	4.000	2.118	0.789	120	0.583	2.538	3.693
10	0.943	84	0.833	4.079	2.193	0.778	121	0.579	2.582	3.996

Combined Trading

	Permit Sector					Credit Sector			
b	q^p	n^p	E^p	p^p	R	q^c	n^c	E^c	p^c
1	0.963	99	0.693	2.467	0.541	0.971	102	0.700	2.100
2	0.941	97	0.695	2.869	0.986	0.945	104	0.698	2.173
3	0.925	95	0.698	3.211	1.361	0.922	106	0.695	2.229
4	0.913	93	0.703	3.508	1.682	0.908	107	0.698	2.286
5	0.904	91	0.708	3.771	1.962	0.902	107	0.706	2.344
6	0.899	89	0.715	4.003	2.206	0.898	107	0.714	2.394
7	0.895	87	0.723	4.211	2.420	0.894	107	0.721	2.436
8	0.894	85	0.731	4.397	2.608	0.890	107	0.727	2.473
9	0.887	84	0.733	4.550	2.776	0.887	107	0.733	2.504
10	0.890	82	0.743	4.705	2.926	0.892	106	0.746	2.544

Welfare

	Separate Schemes			Combined trading		
b	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
1	492.3	491.6	983.9	491.5	492.4	983.9
2	486.6	484.1	970.7	484.1	486.9	971.0
3	482.2	477.6	959.7	477.5	482.7	960.2
4	478.7	471.4	950.2	471.5	479.8	951.2
5	476.0	465.9	941.9	466.0	477.8	943.8
6	473.8	460.8	934.6	461.0	476.4	937.4
7	471.9	456.4	928.3	456.4	475.5	931.9
8	470.4	451.9	922.3	452.2	474.8	927.1
9	469.1	447.7	916.8	448.4	474.5	922.9
10	468.0	444.1	912.1	444.9	474.6	919.4

that more firms can exist in the market. When demand is more elastic, total output decreases more and fewer firms can survive in the market. At some point, demand decreases by so much with an increase in price that the total number of firms decreases compared with no regulation.

It is interesting to see that in general the outcome depends on the elasticity of demand. For example, the higher the elasticity of demand, the lower the emissions quota price, and the larger the difference between the permit and credit price. With a high demand elasticity, a given increase in price results in a relatively large decrease in output and thereby also in emissions. Hence, the price of emissions does not need to be very high to achieve a given reduction in emissions. Credit trading results in a smaller decrease in emissions for a given emissions quota price because of the implicit output subsidy that is inherent in this system. The effect of the output subsidy will be larger, the larger the elasticity is. Hence, the credit price must be higher than the permit price and the difference must be larger when demand is more elastic.

Table 3: Perfect Competition: Elastic Demand

$a = 1$, $K = 1$, $\alpha = 3$, $\beta = 0.01$, $q^0 = 1$, $n^0 = 100$, $E^0 = 1$, $p^0 = 2$, $L = 70$										
	Permit Trading					Credit Trading				
b	q^p	n^p	E^p	p^p	R^p	q^c	n^c	E^c	p^c	R^c
1	0.996	79	0.886	2.213	0.220	0.972	96	0.729	2.066	0.487
2	0.998	75	0.933	2.252	0.257	0.957	94	0.745	2.101	0.848
3	1.003	73	0.959	2.268	0.263	0.944	93	0.753	2.122	1.150
4	1.005	72	0.972	2.276	0.265	0.937	92	0.761	2.138	1.408
5	1.000	72	0.972	2.280	0.280	0.933	91	0.769	2.151	1.634
6	1.008	71	0.986	2.284	0.268	0.931	90	0.778	2.162	1.834
7	1.006	71	0.986	2.286	0.275	0.924	90	0.778	2.169	2.040
8	1.003	71	0.986	2.288	0.281	0.924	89	0.787	2.177	2.205
9	1.002	71	0.986	2.289	0.285	0.919	89	0.787	2.182	2.385
10	1.000	71	0.986	2.290	0.289	0.922	88	0.796	2.189	2.524

Combined Trading

	Permit Sector					Credit Sector			
b	q^p	n^p	E^p	p^p	R	q^c	n^c	E^c	p^c
1	0.991	72	0.839	2.287	0.305	0.991	95	0.838	2.059
2	0.991	64	0.895	2.366	0.385	0.992	93	0.896	2.077
3	0.993	60	0.923	2.404	0.419	0.994	92	0.924	2.086
4	0.991	58	0.940	2.423	0.435	0.997	91	0.942	2.093
5	0.998	56	0.954	2.441	0.445	0.996	91	0.952	2.094
6	0.996	56	0.958	2.442	0.451	1.000	90	0.962	2.100
7	0.997	55	0.964	2.452	0.459	0.999	90	0.967	2.101
8	1.000	54	0.972	2.460	0.459	0.999	90	0.971	2.101
9	0.997	54	0.971	2.462	0.467	0.999	90	0.973	2.101
10	1.001	53	0.978	2.469	0.467	0.999	90	0.976	2.101

Welfare

	Separate Schemes			Combined trading		
b	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
1	46.77	44.03	90.80	44.22	47.61	91.83
2	46.21	40.87	87.08	42.12	47.98	90.09
3	45.99	38.73	84.72	40.94	48.28	89.22
4	45.87	37.28	83.15	40.35	48.49	88.84
5	45.80	36.30	82.10	39.72	48.66	88.38
6	45.75	35.63	81.38	39.74	48.74	88.48
7	45.71	34.67	80.39	39.37	48.82	88.19
8	45.69	34.40	80.09	39.08	48.90	87.98
9	45.67	33.69	79.36	39.02	48.94	87.96
10	45.65	33.66	79.31	38.69	49.00	87.69

For combined trading, the simulations show that in general, permits flow to the credit market and the resulting emission quota price lies in between the original permit and credit prices. The result is an increase in production in the credit sector, both per firm and in total, and a decrease in production in the permit sector. Combining the two schemes therefore leads to even larger inefficiencies in that credit sector production is increased above the already too high level. However, here as well the integer constraint on the number of firms produces deviations from the theoretical analysis of Section 2.1. In several cases the product price in the credit sector is higher under combined trading than under separate schemes. This occurs in Table 1 for $b = 4, 5, 6$, Table 2 for $b = 1, 2$, Table 4 for an emission reduction of 60% and in Table 5 for emission reductions of 30, 60 and 70%. This however does not imply that in these cases, production in the permit sector is stimulated. This occurs only in Table 5 for an emission reduction of 60%. Note that in this case the emissions quota price for combined trading lies

Table 4: Perfect Competition: Change in emission reduction 1

$a=1,\ b=1,\ K=1,\ \alpha=102,\ \beta=1,\ q^0=1,\ n^0=100,\ E^0=1,\ p^0=2$										
	Permit Trading					Credit Trading				
EmRed	q^p	n^p	E^p	p^p	R^p	q^c	n^c	E^c	p^c	R^c
10	0.998	100	0.900	2.192	0.196	1.000	100	0.900	2.020	0.200
20	0.987	101	0.792	2.362	0.389	0.990	101	0.792	2.058	0.395
30	0.966	103	0.680	2.505	0.573	0.961	104	0.673	2.093	0.575
40	0.938	106	0.566	2.618	0.743	0.933	107	0.561	2.163	0.745
50	0.903	110	0.455	2.702	0.896	0.899	111	0.450	2.245	0.897
60	0.863	115	0.348	2.756	1.030	0.859	116	0.345	2.334	1.029
70	0.827	120	0.250	2.807	1.153	0.823	121	0.248	2.449	1.150
80	0.787	126	0.159	2.831	1.257	0.783	127	0.158	2.565	1.251
90	0.746	133	0.075	2.832	1.341	0.747	133	0.075	2.701	1.343
100	0.708	140	0.000	2.833	1.417	0.708	140	0.000	2.833	1.417

Combined Trading

	Permit Sector					Credit Sector			
EmRed	q^p	n^p	E^p	p^p	R	q^c	n^c	E^c	p^c
10	0.998	100	0.899	2.194	0.198	1.000	100	0.901	2.019
20	0.987	101	0.791	2.365	0.392	0.990	101	0.794	2.057
30	0.966	103	0.679	2.506	0.574	0.961	104	0.674	2.093
40	0.929	107	0.559	2.599	0.741	0.933	107	0.563	2.162
50	0.903	110	0.456	2.699	0.893	0.899	111	0.452	2.243
60	0.863	115	0.348	2.756	1.030	0.859	116	0.344	2.335
70	0.820	121	0.247	2.787	1.147	0.823	121	0.249	2.447
80	0.787	126	0.163	2.823	1.249	0.783	127	0.159	2.564
90	0.746	133	0.075	2.833	1.342	0.747	133	0.076	2.700
100	0.708	140	0.000	2.833	1.417	0.708	140	0.000	2.833

Welfare

	Separate Schemes			Combined trading		
EmRed	PT	CT	Tot	CPT	CCT	Tot
10	4999	4999	9998	4999	4999	9998
20	4996	4996	9992	4996	4996	9992
30	4991	4991	9983	4991	4991	9983
40	4985	4985	9969	4985	4985	9969
50	4977	4977	9953	4977	4977	9953
60	4967	4967	9934	4967	4967	9934
70	4956	4956	9912	4956	4956	9912
80	4944	4944	9888	4944	4944	9888
90	4931	4931	9863	4931	4931	9863
100	4918	4918	9835	4918	4918	9835

between the permit and credit price. Note also that in the same table for emission reductions of 80 and 90% the product price in the permit sector is lower under combined trading than in the separate scheme. In these two cases, both sectors are stimulated as a result of combining them. Another irregularity is that in certain cases the emissions quota price for combined trading lies below both the permit and credit price for the separate schemes. This is the case in Table 4 for emission reductions of 40, 50, 70 and 80% and in Table 5 for an emission reduction of 90%. The explanation for these differences with the results of Section 2.1 is basically the same as the one given for the separate schemes. When the number of firms is an integer, production occurs in a point away from the lowest cost point and production under one scheme may be further away from this point than for the other scheme. This makes all of the above-mentioned anomalies possible.

We showed in Section 2.3 that permit trading always leads to higher welfare than credit

Table 5: Perfect Competition: Change in emission reduction 2

$a=1,\ b=1,\ K=1,\ \alpha=12,\ \beta=0.1,\ q^0=1,\ n^0=100,\ E^0=1,\ p^0=2$										
	Permit Trading					Credit Trading				
EmRed	q^p	n^p	E^p	p^p	R^p	q^c	n^c	E^c	p^c	R^c
10	1.003	98	0.918	2.174	0.169	0.998	100	0.900	2.016	0.197
20	0.988	98	0.816	2.319	0.343	0.985	101	0.792	2.047	0.387
30	0.973	98	0.714	2.464	0.518	0.962	103	0.680	2.090	0.565
40	0.943	100	0.600	2.571	0.686	0.937	105	0.571	2.160	0.731
50	0.907	103	0.485	2.657	0.843	0.904	108	0.463	2.238	0.882
60	0.874	106	0.377	2.740	0.993	0.864	112	0.357	2.323	1.014
70	0.831	111	0.270	2.782	1.121	0.825	116	0.259	2.428	1.133
80	0.791	116	0.172	2.821	1.238	0.787	120	0.167	2.553	1.241
90	0.751	122	0.082	2.840	1.338	0.750	124	0.081	2.696	1.339
100	0.710	129	0.000	2.840	1.420	0.710	129	0.000	2.840	1.420

Combined Trading

	Permit Sector					Credit Sector			
EmRed	q^p	n^p	E^p	p^p	R	q^c	n^c	E^c	p^c
10	1.002	98	0.911	2.185	0.182	0.999	100	0.908	2.015
20	0.986	98	0.804	2.336	0.364	0.986	101	0.804	2.043
30	0.963	99	0.693	2.467	0.541	0.971	102	0.700	2.100
40	0.941	100	0.587	2.590	0.708	0.938	105	0.584	2.152
50	0.906	103	0.474	2.673	0.862	0.905	108	0.474	2.230
60	0.866	107	0.364	2.735	1.003	0.871	111	0.370	2.330
70	0.830	111	0.265	2.789	1.129	0.832	115	0.267	2.438
80	0.791	116	0.173	2.820	1.238	0.788	120	0.169	2.551
90	0.746	123	0.079	2.825	1.333	0.751	124	0.084	2.691
100	0.710	129	0.000	2.840	1.420	0.710	129	0.000	2.840

Welfare

	Separate Schemes			Combined trading		
EmRed	PT	CT	Tot	CPT	CCT	Tot
10	499.2	499.0	998.2	499.0	499.2	998.2
20	496.6	496.2	992.8	496.2	496.6	992.8
30	492.3	491.6	983.9	491.5	492.4	983.9
40	486.3	485.4	971.7	485.4	486.3	971.7
50	478.6	477.7	956.4	477.7	478.7	956.3
60	469.5	468.6	938.1	468.5	469.7	938.1
70	458.9	458.3	917.2	458.3	459.1	917.4
80	447.1	446.8	894.0	447.2	447.1	894.3
90	434.3	434.2	868.6	434.0	434.8	868.8
100	420.6	420.6	841.2	420.9	420.9	841.7

trading. This is borne out in Tables 1 through 6. A more interesting question is whether combining a permit and a credit trading scheme will lead to an increase or a decrease in welfare. In Section 2.4 we showed that both results are possible. In our simulations, the only instance where welfare decreases as a result of combining the two schemes is given in Table 5 for an emission reduction of 50%. In all other cases, welfare either does not change or increases when the two schemes are combined. This shows that even small differences in marginal abatement costs can trigger an increase in welfare from combining the two schemes.

3.2 Imperfect Competition

Our simulation here consists basically of two cases with different demand functions. For both cases, b, a measure for the marginal abatement costs in equation (36), and the emission reduction

Table 6: Perfect Competition: Change in emission reduction 3

$a = 1$, $b = 1$, $K = 1$, $\alpha = 3$, $\beta = 0.01$, $q^0 = 1$, $n^0 = 100$, $E^0 = 1$, $p^0 = 2$										
	Permit Trading					Credit Trading				
EmRed	q^p	n^p	E^p	p^p	R^p	q^c	n^c	E^c	p^c	R^c
10	1.001	93	0.968	2.069	0.067	0.998	99	0.909	2.012	0.178
20	1.000	86	0.930	2.140	0.140	0.987	98	0.816	2.033	0.341
30	0.996	79	0.886	2.213	0.220	0.972	96	0.729	2.067	0.486
40	0.989	72	0.833	2.288	0.311	0.951	94	0.638	2.106	0.625
50	0.983	64	0.781	2.371	0.404	0.930	90	0.556	2.163	0.750
60	0.971	56	0.714	2.456	0.514	0.901	86	0.465	2.225	0.872
70	0.949	48	0.625	2.545	0.647	0.870	80	0.375	2.304	0.990
80	0.917	39	0.513	2.642	0.809	0.836	71	0.282	2.407	1.108
90	0.860	29	0.345	2.751	1.031	0.789	58	0.172	2.542	1.234
100	0.708	24	0.000	2.830	1.415	0.708	24	0.000	2.830	1.415

Combined Trading

	Permit Sector					Credit Sector			
EmRed	q^p	n^p	E^p	p^p	R	q^c	n^c	E^c	p^c
10	1.001	90	0.953	2.099	0.097	1.000	99	0.952	2.010
20	0.997	81	0.898	2.192	0.198	0.999	97	0.900	2.031
30	0.991	72	0.839	2.287	0.305	0.991	95	0.838	2.059
40	0.978	64	0.769	2.374	0.418	0.980	92	0.770	2.099
50	0.967	55	0.700	2.468	0.534	0.965	88	0.699	2.150
60	0.947	47	0.616	2.555	0.661	0.946	83	0.615	2.215
70	0.920	39	0.519	2.641	0.801	0.917	77	0.516	2.294
80	0.879	32	0.399	2.719	0.960	0.881	68	0.401	2.401
90	0.818	26	0.243	2.787	1.151	0.820	56	0.245	2.541
100	0.708	24	0.000	2.830	1.415	0.708	24	0.000	2.830

Welfare

	Separate Schemes			Combined trading		
EmRed	PT	CT	Tot	CPT	CCT	Tot
10	49.66	49.21	98.87	49.30	49.76	99.06
20	48.60	47.08	95.68	47.36	49.00	96.36
30	46.77	44.03	90.80	44.22	47.61	91.83
40	44.10	40.04	84.14	40.17	45.45	85.61
50	40.50	35.60	76.10	35.07	42.50	77.57
60	35.85	30.27	66.13	29.33	38.37	67.70
70	30.01	24.42	54.43	22.94	32.78	55.72
80	22.73	18.02	40.75	16.33	25.31	41.64
90	13.56	10.66	24.22	9.534	15.02	24.55
100	1.472	1.472	2.943	1.472	1.472	2.944

level are varied to yield different results. Furthermore, the welfare levels and some special cases under permit and credit trading are discussed. The simulation results for imperfect competition are shown in Tables 7 to 13. In Tables 7, 9 and 11 the inverse demand function is relatively flat, while in the other Tables the slope is relatively steep. In all cases, there are four firms when there is no regulation. However, because the demand functions are different, firm production and emissions are different in the two cases.

The first main result from the simulations is that the number of firms under credit trading is always at least as high as that under permit trading. This result is expected since the demand function is linear, so that inequality (21) holds. Furthermore, product price p is always lower under credit trading. This confirms the results of the analysis in Section 2. The simulations also confirm the results of the general analysis for the case where the number of firms is equal under the two schemes. Here, firm and total output are higher under credit trading and the

Table 7: Imperfect Competition 1

$a = 1,\ K = 100,\ \alpha = 50,\ \beta = 1$

$q^0 = 7.14,\ n^0 = 4,\ E^0 = 7.14,\ p^0 = 21.43,\ \pi^0 = 2.04\ L = 20$

	Permit Trading						Credit Trading					
b	q^p	n^p	E^p	p^p	π^p	R^p	q^c	n^c	E^c	p^c	π^c	R^c
1	7.92	3	6.67	26.25	26.91	2.50	6.90	4	5.00	22.42	3.44	3.79
2	7.67	3	6.67	27.00	19.56	4.00	6.71	4	5.00	23.15	4.50	6.85
3	7.50	3	6.67	27.50	14.58	5.00	6.57	4	5.00	23.73	5.36	9.40
4	7.38	3	6.67	27.86	11.00	5.71	6.45	4	5.00	24.20	6.09	11.60
5	7.29	3	6.67	28.13	8.29	6.25	6.35	4	5.00	24.59	6.73	13.52
6	7.22	3	6.67	28.33	6.17	6.67	6.27	4	5.00	24.92	7.29	15.23
7	7.17	3	6.67	28.50	4.47	7.00	6.20	4	5.00	25.21	7.80	16.76
8	7.12	3	6.67	28.64	3.08	7.27	6.13	4	5.00	25.46	8.26	18.15
9	7.08	3	6.67	28.75	1.91	7.50	6.08	4	5.00	25.68	8.69	19.43
10	7.05	3	6.67	28.85	0.92	7.69	6.03	4	5.00	25.88	9.08	20.60
20	10.00	2	10.00	30.00	100.00	0.00	5.72	4	5.00	27.11	11.98	28.87
50	10.00	2	10.00	30.00	100.00	0.00	5.40	4	5.00	28.40	16.22	39.95

Combined Trading

	Permit Sector						Credit Sector				
b	q^p	n^p	E^p	p^p	π^p	R	q^c	n^c	E^c	p^c	π^c
1	7.80	3	6.21	26.59	24.30	3.18	6.93	4	5.34	22.26	2.67
2	7.43	3	6.08	27.71	14.10	5.42	6.80	4	5.44	22.82	2.81
3	7.15	3	5.98	28.54	6.54	7.08	6.70	4	5.52	23.21	2.74
4	6.94	3	5.89	29.18	0.69	8.36	6.62	4	5.58	23.50	2.59
5	8.33	2	7.49	33.34	42.19	8.36	6.62	4	5.79	23.50	1.72
6	8.33	2	7.63	33.34	41.61	8.36	6.62	4	5.93	23.50	1.13
7	8.33	2	7.73	33.34	41.20	8.36	6.62	4	6.03	23.50	0.72
8	8.32	2	7.80	33.35	40.78	8.38	6.62	4	6.10	23.51	0.41
9	8.25	2	7.77	33.50	38.29	8.74	6.60	4	6.12	23.59	0.26
10	8.19	2	7.74	33.62	36.14	9.06	6.59	4	6.13	23.66	0.12
20	7.04	3	6.85	28.87	0.00	7.73	7.78	3	7.59	26.66	39.01
50	7.06	3	6.98	28.82	0.00	7.64	7.79	3	7.71	26.64	38.54

Welfare

	Separate Schemes			Combined trading		
b	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
1	412.98	394.52	807.50	406.00	399.31	805.31
2	403.40	378.18	781.58	389.53	390.60	780.12
3	396.92	366.57	763.50	376.65	384.75	761.40
4	392.47	357.13	749.60	366.54	380.54	747.08
5	389.15	349.55	738.71	348.39	384.06	732.45
6	386.48	343.54	730.02	349.56	386.42	735.98
7	384.79	338.52	723.31	350.40	388.10	738.50
8	382.93	333.97	716.90	350.70	389.32	740.02
9	381.41	330.41	711.82	348.60	388.85	737.46
10	380.40	327.23	707.63	346.65	388.66	735.31
20	400.00	309.79	709.79	382.02	410.87	792.89
50	400.00	298.08	698.08	384.21	412.53	796.74

credit price is higher than the permit price.

Another general result is that the number of firms can increase or decrease as a result of regulation. This holds under both instruments. As with perfect competition, the number of firms will increase when demand is very inelastic (Tables 8 and 12) and decrease when demand is more elastic (Tables 7 and 9). The explanation for this is the same as under perfect competition: regulation lowers the optimal production level, and more so under credit trading than under permit trading, while demand decreases more, the more elastic demand is. This implies that there will be room for more firms the more inelastic demand is.

Table 8: Imperfect Competition 2

$a = 1$, $K = 100$, $\alpha = 150$, $\beta = 6.6$
$q^0 = 4.29$, $n^0 = 4$, $E^0 = 4.29$, $p^0 = 36.86$, $\pi^0 = 39.59$ $L = 12.00$

	Permit Trading						Credit Trading					
b	q^p	n^p	E^p	p^p	π^p	R^p	q^c	n^c	E^c	p^c	π^c	R^c
1	4.22	4	3.00	38.69	36.58	2.43	4.25	4	3.00	37.75	40.85	2.50
2	4.15	4	3.00	40.34	33.80	4.62	3.55	5	2.40	32.69	0.92	4.62
3	4.10	4	3.00	41.82	31.21	6.59	3.53	5	2.40	33.47	1.87	6.79
4	4.05	4	3.00	43.17	28.83	8.37	3.51	5	2.40	34.20	2.77	8.87
5	4.00	4	3.00	44.40	26.60	10.00	3.49	5	2.40	34.89	3.62	10.88
6	3.96	4	3.00	45.52	24.53	11.49	3.47	5	2.40	35.55	4.42	12.82
7	3.92	4	3.00	46.56	22.59	12.86	3.45	5	2.40	36.18	5.17	14.69
8	3.88	4	3.00	47.51	20.78	14.12	3.43	5	2.40	36.77	5.90	16.50
9	3.85	4	3.00	48.38	19.08	15.28	3.41	5	2.40	37.34	6.58	18.25
10	3.82	4	3.00	49.20	17.49	16.36	3.40	5	2.40	37.89	7.24	19.95
20	3.60	4	3.00	54.96	5.70	24.00	3.26	5	2.40	42.29	12.47	34.55
50	4.28	3	4.00	65.19	43.47	28.35	3.04	5	2.40	49.70	21.36	63.95

Combined Trading

	Permit Sector						Credit Sector				
b	q^p	n^p	E^p	p^p	π^p	R	q^c	n^c	E^c	p^c	π^c
1	4.22	4	2.99	38.71	36.57	2.45	4.25	4	3.03	37.73	40.79
2	4.15	4	3.00	40.34	33.80	4.62	3.55	5	2.40	32.69	0.92
3	4.09	4	2.98	41.91	31.15	6.69	3.53	5	2.42	33.43	1.77
4	4.04	4	2.96	43.37	28.64	8.64	3.51	5	2.43	34.11	2.53
5	3.99	4	2.94	44.74	26.28	10.46	3.49	5	2.45	34.74	3.19
6	3.94	4	2.92	46.04	24.03	12.17	3.47	5	2.46	35.33	3.78
7	3.89	4	2.91	47.25	21.90	13.78	3.46	5	2.47	35.87	4.30
8	3.85	4	2.89	48.40	19.88	15.30	3.44	5	2.49	36.38	4.76
9	3.81	4	2.88	49.49	17.95	16.74	3.43	5	2.50	36.85	5.17
10	3.77	4	2.86	50.52	16.12	18.11	3.42	5	2.51	37.30	5.53
20	3.47	4	2.75	58.47	1.62	28.65	3.32	5	2.60	40.58	7.58
50	3.79	3	3.37	74.88	18.32	42.25	3.20	5	2.78	44.41	7.01

Welfare

	Separate Schemes			Combined trading		
b	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
1	1115,36	1117,38	2232,73	1115,43	1117,50	2232,93
2	1100,35	1045,14	2145,49	1100,35	1045,14	2145,49
3	1091,16	1037,66	2128,83	1088,13	1037,98	2126,11
4	1081,43	1030,11	2111,54	1078,48	1030,64	2109,12
5	1071,20	1022,56	2093,76	1068,29	1023,92	2092,21
6	1063,67	1015,09	2078,77	1057,73	1016,93	2074,66
7	1055,87	1007,70	2063,57	1047,19	1013,61	2060,80
8	1047,68	1000,29	2047,97	1038,90	1007,60	2046,50
9	1042,23	993,03	2035,25	1030,91	1004,49	2035,41
10	1036,62	989,27	2025,89	1021,95	1001,53	2023,47
20	995,07	940,07	1935,14	957,15	974,86	1932,01
50	1014,80	869,11	1883,92	908,89	959,98	1868,87

For the case where the number of firms is higher under credit trading than under permit trading, the general analysis did not yield many clear results. In the simulations, firm output is always lower under credit trading than under permit trading. However, this is not a conclusive result since we only have a few simulations.

As already mentioned, the product price is lower under credit trading than under permit trading. Furthermore, the product price increases with b (see Tables 7 and 8). Since b is the parameter controlling the size of the marginal abatement costs, this result is expected. One might also expect that the product price is decreasing in total emissions L. Although this holds

Table 9: Imperfect Competition 3

$a = 1$, $b = 1$, $K = 100$, $\alpha = 50$, $\beta = 1$, $q^0 = 7.14$, $n^0 = 4$, $E^0 = 7.14$, $p^0 = 21.43$, $\pi^0 = 2.04$

	Permit Trading						Credit Trading					
%Red	q^p	n^p	E^p	p^p	π^p	R^p	q^c	n^c	E^c	p^c	π^c	R^c
10	—*	—	—	—	—	—	7.08	4	6.43	21.67	2.87	1.31
20	8.16	3	7.62	25.54	33.29	1.07	7.00	4	5.71	22.00	3.34	2.57
30	7.91	3	6.67	26.25	26.91	2.50	6.90	4	5.00	22.42	3.44	3.79
40	7.68	3	5.71	26.96	21.78	3.93	6.77	4	4.29	22.92	3.16	4.97
50	7.44	3	4.76	27.68	17.90	5.36	6.62	4	3.57	23.51	2.51	6.10
60	7.20	3	3.81	28.39	15.26	6.79	6.46	4	2.86	24.18	1.45	7.20
70	6.96	3	2.86	29.11	13.87	8.21	—*	—	—	—	—	—
80	6.73	3	1.90	29.82	13.73	9.64	6.96	3	1.90	29.13	28.73	10.10
90	6.49	3	0.95	30.54	14.83	11.07	6.62	3	0.95	30.13	23.52	11.34
100	6.25	3	0.00	31.25	17.19	12.50	6.25	3	0.00	31.25	17.19	12.50

Combined Trading

	Permit Sector						Credit Sector				
%Red	q^p	n^p	E^p	p^p	π^p	R	q^c	n^c	E^c	p^c	π^c
10	8.25	3	7.99	25.26	36.08	0.52	7.12	4	6.86	21.52	2.26
20	8.02	3	7.09	25.93	29.61	1.86	7.04	4	6.11	21.84	2.62
30	7.80	3	6.21	26.59	24.30	3.18	6.93	4	5.34	22.26	2.67
40	7.59	3	5.35	27.24	20.12	4.48	6.81	4	4.56	22.78	2.44
50	7.37	3	4.50	27.88	17.03	5.76	6.65	4	3.77	23.39	1.92
60	7.17	3	3.66	28.50	14.96	7.01	6.47	4	2.97	24.11	1.09
70	6.96	3	2.83	29.13	13.85	8.26	7.32	3	3.18	28.06	31.95
80	6.69	3	1.76	29.93	13.82	9.87	6.99	3	2.06	29.04	28.26
90	6.47	3	0.86	30.60	15.00	11.20	6.64	3	1.04	30.07	23.24
100	6.25	3	0.00	31.25	17.19	12.50	6.25	3	0.00	31.25	17.19

Welfare

	Separate Schemes			Combined trading		
%Red	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
10	—*	412.86	—	413.87	415.37	829.24
20	423.60	405.40	829.00	418.10	409.77	827.87
30	412.76	394.16	806.92	406.20	399.71	805.90
40	398.01	379.32	777.33	391.23	385.20	776.43
50	379.34	360.99	740.33	373.40	366.24	739.64
60	356.77	339.23	696.00	352.90	342.70	695.60
70	330.28	—	—	329.33	344.73	674.06
80	299.88	303.97	603.85	294.78	308.95	603.72
90	265.57	268.02	533.58	262.16	271.38	533.54
100	227.34	227.34	454.69	227.34	227.34	454.69

* — indicates that the emission reduction level is not obtainable (see Tables 10 and 11).

as long as the number of firms remains the same or decreases, it may not hold when the number of firms increases. This is shown in Table 12, for both permit trading and credit trading, where the product price falls when the number of firms increases, even though the emission reduction level is higher. Here, two effects are at play. First, the higher emission reduction level will increase marginal abatement costs. However, if at the same time profits rise with stricter policy, as is the case here, entry will take place at some point. As is shown in appendix B, entry leads to higher total output and lower product price. In some cases, the output-increasing effect of entry is larger than the cost-increasing effect of stricter policy, so that prices fall.

As with perfect competition, the permit price may be higher than the credit price. This is shown in Table 12 for emission reductions of 40 to 80%. Notice that at these emission reduction levels there are four firms in the permit sector and five in the credit sector. At the same

Table 10: Some L not obtainable with permit trading

$a=1$, $b=1$, $K=100$, $\alpha=50$, $\beta=1$, $q^0=7.14$, $n^0=4$, $E^0=7.14$, $p^0=21.43$, $\pi^0=2.04$								
% em.red.	L	$\sum E$	q^p	n^p	E^p	p^p	π^p	R^p
4.6729	27.2363	27.2363	7.0687	4	6.8091	21.7253	0.0000	0.5192
4.6732	27.2362	25.0000	8.3333	3	8.3333	25.0000	38.8889	0.0000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
12.4999	25.0000	25.0000	8.3333	3	8.3333	25.0000	38.8889	0.0000
12.5006	24.9998	24.9998	8.3333	3	8.3333	25.0000	38.8884	0.0001

Table 11: Some L are not obtainable with credit trading

$a=1$, $b=1$, $K=100$, $\alpha=50$, $\beta=1$, $q^0=7.14$, $n^0=4$, $E^0=7.14$, $p^0=21.43$, $\pi^0=2.04$								
$\bar{e}$	% em.red.	L	q^c	n^c	E^c	p^c	π^c	R^c
0.3438	69.8225	8.6221	6.2703	4	2.1555	24.9187	0.0000	8.2296
0.3438	74.2603	7.3542	7.1310	3	2.4514	28.6071	31.2473	9.3591

time, profits are high in the permit sector and low in the credit sector. This implies that firm production in the credit sector is close to the zero-profit point, while that in the permit sector occurs at a less efficient scale. In this case, firm production in the permit sector takes place at such an inefficient level that marginal abatement costs become higher than in the credit sector, even though credit trading is a less efficient form of regulation. Note also that the permit price falls as we move from 80 to 90% emission reduction. At 90% a new firm has entered the permit sector and firm production is suddenly very close to the zero-profit level, and therefore much more efficient than before. Hence, with imperfect competition, firm entry may lead to lower marginal abatement costs and thereby lower emission quota prices.

We now turn to the effect of the two schemes on profits. In Tables 7 and 8, for a given number of firms, under permit trading profits decrease in b, while under credit trading they increase in b. Furthermore, with the number of firms constant, regulation leads to a decrease in profits with permit trading and to an increase with credit trading. Basically, regulation has two effects. First of all, regulation increases production costs and thereby lowers profits. Second, it lowers firm production. As long as the number of firms remains constant, this also means lower total production and thereby higher price. Since production under oligopoly is higher than the joint profit-maximizing (monopoly) level, the latter effect gives higher profits for all firms. The simulations show that under permit trading the former effect is stronger than the latter, while the reverse is the case under credit trading. The intuition for this is that under permit trading, output is already closer to the monopoly level than under credit trading. Reducing output will then have a smaller positive effect on profits under permit trading than under credit trading.

The effect of decreasing L on profits depends on the level of L. For permit trading profits first fall given n, and then rise as L diminishes (Tables 9 and 12). Table 9 shows the reverse happening for credit trading, while in Table 12 profits rise continually with lower L. With a b higher than 3.3, credit trading always results initially in a rise in profit and then a decline with

Table 12: Imperfect Competition 4

$a = 1,\ b = 1,\ K = 100,\ \alpha = 150,\ \beta = 6.6,\ q^0 = 4.29,\ n^0 = 4,\ E^0 = 4.29,\ p^0 = 36.86,\ \pi^0 = 39.59$												
	Permit Trading						Credit Trading					
%Red	q^p	n^p	E^p	p^p	π^p	R^p	q^c	n^c	E^c	p^c	π^c	R^c
10	4.26	4	3.86	37.47	38.25	0.81	4.28	4	3.86	37.07	40.08	0.85
20	4.24	4	3.43	38.08	37.25	1.62	4.27	4	3.43	37.36	40.49	1.68
30	4.22	4	3.00	38.69	36.58	2.43	4.25	4	3.00	37.75	40.85	2.50
40	4.19	4	2.57	39.30	36.25	3.24	3.57	5	2.06	32.30	0.20	3.02
50	4.17	4	2.14	39.92	36.26	4.05	3.55	5	1.71	32.80	0.50	3.67
60	4.15	4	1.71	40.53	36.60	4.86	3.53	5	1.37	33.38	0.78	4.33
70	4.12	4	1.29	41.14	37.28	5.66	3.51	5	1.03	34.03	1.06	4.97
80	4.10	4	0.86	41.75	38.30	6.49	3.49	5	0.69	34.76	1.32	5.61
90	3.46	5	0.34	35.95	0.47	6.23	3.47	5	0.34	35.57	1.57	6.25
100	3.44	5	0.00	36.47	1.79	6.88	3.44	5	0.00	36.47	1.79	6.88

Combined Trading

	Permit Sector						Credit Sector				
%Red	q^p	n^p	E^p	p^p	π^p	R	q^c	n^c	E^c	p^c	π^c
10	4.26	4	3.85	37.48	38.23	0.83	4.28	4	3.87	37.06	40.06
20	4.24	4	3.42	38.10	37.22	1.65	4.27	4	3.44	37.35	40.47
30	4.22	4	2.99	38.71	36.57	2.45	4.25	4	3.03	37.73	40.79
40	4.20	4	2.64	39.21	36.28	3.12	3.57	5	2.01	32.34	0.33
50	4.18	4	2.25	39.76	36.22	3.85	3.55	5	1.63	32.88	0.74
60	4.16	4	1.87	40.30	36.44	4.57	3.53	5	1.25	33.51	1.18
70	4.14	4	1.49	40.85	36.91	5.29	3.51	5	0.87	34.22	1.63
80	4.12	4	1.13	41.35	37.60	5.96	3.49	5	0.50	34.99	2.01
90	3.46	5	0.34	35.96	0.49	6.24	3.47	5	0.35	35.57	1.54
100	3.44	5	0.00	36.47	1.79	6.88	3.44	5	0.00	36.47	1.79

Welfare

	Separate Schemes			Combined trading		
%Red	**PT**	**CT**	**Tot**	**CPT**	**CCT**	**Tot**
10	1124.85	1126.57	2251.42	1124.78	1126.62	2251.40
20	1120.17	1123.18	2243.35	1119.99	1123.31	2243.30
30	1114.11	1118.02	2232.13	1113.95	1118.36	2232.32
40	1106.67	1050.51	2157.18	1107.89	1049.57	2157.47
50	1097.86	1043.10	2140.96	1100.26	1041.18	2141.44
60	1087.67	1034.32	2122.00	1091.56	1031.10	2122.66
70	1076.11	1024.17	2100.28	1081.82	1019.34	2101.17
80	1063.17	1012.65	2075.82	1071.70	1006.61	2078.31
90	998.46	999.74	1998.20	998.26	999.97	1998.22
100	985.44	985.44	1970.88	985.44	985.44	1970.88

lower L (not shown).

In Propositions 5 and 6 we showed that under both schemes it is possible that certain emission levels cannot be attained. This is illustrated in Tables 9 to 11. As Table 10 shows, under the given circumstances, emission reductions between 4.67% and 12.5% are not obtainable with permit trading. The reason is that at emission reduction level 4.67% the number of firms in the market decreases to three and the emission limit becomes non-binding. The three remaining firms emit a total amount of 25 without regulation, which corresponds to an emission reduction of 12.5%. Only at an emission reduction level higher than 12.5% does the emission limit become binding again.

For credit trading something similar happens. As the relative standard is tightened, exit may occur, as is shown in Tables 9 and 11. As a result, total output decreases, but since the relative standard is fixed at this level, total emissions will decrease as well. In Table 11 this

Table 13: Some L can be obtained with different $\bar{e}$

$a = 1$, $b = 1$, $K = 100$, $\alpha = 150$, $\beta = 6.6$								
$q^0 = 4.29$, $n^0 = 4$, $E^0 = 4.29$, $p^0 = 36.86$, $\pi^0 = 39.59$								
Credit Trading								
$\bar{e}$	*%.red.*	q^c	n^c	E^c	p^c	π^c	R^c	L
0.6730	33.317	4.246	4	2.858	37.895	40.956	2.777	11.431
0.6670	33.928	4.245	4	2.832	37.923	40.974	2.827	11.327
0.6610	34.539	4.244	4	2.806	37.952	40.993	2.878	11.222
0.6550	35.150	4.243	4	2.779	37.981	41.011	2.928	11.117
0.6490	35.761	4.242	4	2.753	38.010	41.028	2.978	11.012
0.6430	36.372	4.241	4	2.727	38.040	41.046	3.028	10.908
0.6396	36.715	4.240	4	2.712	38.057	41.055	3.056	10.849
0.6396	33.296	3.576	5	2.287	32.008	0.000	2.577	11.435
0.6370	33.576	3.575	5	2.277	32.019	0.009	2.596	11.387
0.6310	34.217	3.574	5	2.255	32.046	0.028	2.638	11.277
0.6250	34.857	3.575	5	2.234	32.073	0.047	2.680	11.167
0.6190	35.497	3.573	5	2.212	32.100	0.067	2.722	11.058
0.6130	36.137	3.572	5	2.190	32.127	0.086	2.765	10.948
0.6070	36.777	3.571	5	2.168	32.155	0.105	2.807	10.838

happens when the relative standard is 0.3438. Here, profits become zero and a firm will exit. In this case, emission reductions between 69.82% and 74.26% are unobtainable.

Under credit trading it is also possible that certain emission levels can be reached by two different relative standards (see Proposition 6). This is illustrated in Table 13 which shows what happens as the relative standard is tightened from 0.673 to 0.607. At first, profits increase as the emission limit decreases. Then, when the relative standard is 0.6396, profits become so large that entry occurs. This results in an increase in total output. Since the relative standard determines allowed emissions per unit of output, this also implies that total emissions will increase, which is also shown in the Table. Only at a relative standard of about 0.61 are total emissions back at the level where entry occurred. Table 13 shows that emission reduction percentages between 33.3 and 36.72 can be attained with two different relative standards.

In all cases, combining the two emissions trading schemes leads to a stimulation of the sector with the highest quota price at the expense of the other sector. In most cases, this means that the credit sector is stimulated. Only in Table 12 for emission reductions of 40 to 80% is the permit sector stimulated since here the permit price is higher than the credit price.

One of the unresolved issues is which instrument leads to highest welfare. As a glance at Tables 7 through 12 shows, it is usually permit trading that leads to higher welfare. Credit trading leads to higher welfare only in Table 8 for $b = 1$, Table 9 for emission reductions of 80 and 90%, and in Table 12 for emission reductions of 10, 20, 30 and 90%. It is worth noting that these are all cases where marginal abatement costs are either very low or very high. At these levels, the difference in abatement costs between permit trading and credit trading is less pronounced and the additional production under credit trading has a larger impact on welfare than the increase in abatement cost.

Combining the two schemes can lead to both an increase or a decrease in welfare. Increases in welfare are shown in Table 7 for $b = 6$ to $b = 50$, Table 8 for $b = 1$ and for $b = 9$ and in

Table 12 for emission reductions of 30 to 90%. In Table 7 the increase in welfare comes from the large saving in abatement costs as a result of combining the schemes. There is a large difference between the permit and the credit price, while the quota price under combined trading is quite close to the permit price in the separate scheme. In Table 12 it should be remembered that here combined trading stimulates the permit sector for emission reductions of 40 to 80%. Here then, welfare increases because the permit sector is stimulated as a result of combining the two schemes.

4 Conclusion

This paper has analyzed and compared two types of emissions trading to see whether they function similarly or differently under two market structures: perfect and imperfect competition. The first type is permit trading, which is emissions trading based on an absolute cap on emissions, while credit trading is based on relative caps on emissions. The major general result is that credit trading leads to higher total output than permit trading. The explanation for this is that in the credit trading scheme, output is subsidized by allowing additional emissions, whereas in a permit trading scheme, additional output requires either extra abatement costs or purchase of permits. This result holds under both perfect and imperfect competition. However, in other respects, the effect of the two schemes may be rather different under perfect and imperfect competition.

The general model shows that under perfect competition, credit trading always leads to higher abatement costs than permit trading. This is the consequence of the higher level of output with credit trading. Since marginal abatement costs are higher with credit trading, the price of credits is higher than the price of permits. The implicit subsidization of output in the credit scheme has consequences for welfare. Since firms get extra credits for free when increasing output, total output in the credit sector is too high. At the margin of production, marginal benefits to the consumer are lower than the actual marginal cost. This implies that the marginal abatement costs are not included fully in the market price of output. The combination of too high output and too high marginal abatement costs makes credit trading an inferior instrument compared with permit trading.

The two schemes can be combined by allowing the use of credits to cover emissions in the permit sector and vice versa. Emissions trading will lead to a uniform price in the two sectors, lowering the price of credits, while raising the price of permits. The lower abatement costs stimulate output in the credit sector, increasing the sector's emissions while the higher abatement costs reduce output and emissions in the permit sector. Consequently, the discrepancy in terms of output and abatement effort between the two sectors will increase by allowing emission trading between them, exacerbating the welfare loss due to overproduction in the credit sector. However, there is also a positive welfare effect. The sale of emission allowances from firms in the permit sector to firms in the credit sector leads to an increase in abatement in the permit sector where marginal abatement costs are relatively low, whereas abatement decreases in the credit sector, where marginal abatement costs are relatively high. The result is that total abatement costs decrease. The savings on total abatement costs can exceed the welfare loss due to higher production in the credit sector. This is most likely to be the case when marginal abatement costs rise sharply and price elasticity of output demand is low. In the reverse case, welfare will decrease.

With imperfect competition, it still holds that under separate schemes, the credit sector has higher output at lower output price, higher marginal abatement costs and a higher price for emission allowances than the permit sector. Combining the two sectors again increases the discrepancy in sector outputs and emissions. However, the welfare impacts are different. With imperfect competition, output is below the welfare-maximizing level. Here the stimulus credit trading gives to output, which is missing in the permit trading scheme, counteracts the output distortion caused by the structure of the market. The positive welfare effect may be such that a credit trading scheme performs better on welfare than a permit scheme. If the separate sectors are linked and the discrepancies in output increase, this may have a positive impact on welfare (which it never has under perfect competition), thus supporting the positive effect of lower abatement costs.

However, the above general conclusions on imperfect competition are only valid when credit and permit trading result in the same number of firms. For the likely case where there are more firms in the credit sector than in the permit sector, the formal proof could not be given and we had to rely on simulations. In all, except one, specific ranges of simulations, the general conclusions are confirmed for the case where credit trading leads to a higher number of firms in the industry than permit trading. The exception is the case where with separate markets, the permit price is higher than the credit price. The anomaly seems to reflect the impact of entry and exit of firms when there are few incumbents.

Previous contributions have largely ignored the constraint that the number of firms must be an integer. Taking this constraint into account has particulary dramatic consequences under imperfect competition. We find that it may be impossible to implement certain levels of total industry emissions with permit or credit trading. It can also occur that there are multiple levels of the relative standard that achieve the same level of industry emissions.

The major message of this paper for policy makers is that under imperfect competition, one cannot in general say that credit trading is an inefficient instrument.

We have assumed that the government sets its instrument such that an absolute limit on emissions is reached. This may be unrealistic, especially for the case of relative standards and credit trading, since the government may have too little information to set the standard correctly. Another issue that would warrant further research is how the instruments work when firms are heterogeneous. In this paper, firms are homogeneous and therefore there is no trading in the separate schemes.

A Comparative Statics for Perfect Competition

In this Appendix, the effects on output per firm q, emission level per firm E, product price p and number of firms n of a change in the total limit on emissions L will be derived. Assuming a change from a non-binding limit to a limit that is just binding will allow us to analyze the effect of the introduction of regulation.

A.1 Permit Trading

A.1.1 Short Run

In the short run, the following conditions must hold under permit trading

$$p = C_q \tag{38}$$

$$-C_E = R^p \tag{39}$$

$$p = p(nq) \tag{40}$$

Differentiating equations (38)-(40) totally with respect to E gives

$$\frac{dp}{dE} - C_{qE} - C_{qq}\frac{dq}{dE} = 0 \tag{41}$$

$$-C_{EE} - C_{qE}\frac{dq}{dE} = \frac{dR}{dE} \tag{42}$$

$$\frac{dp}{dE} = np'\frac{dq}{dE} \tag{43}$$

The result is

$$\frac{dq^p}{dE} = \frac{C_{qE}}{np' - C_{qq}} > 0 \tag{44}$$

$$\frac{dR^p}{dE} = -\left(\frac{np'C_{EE} + {C_{qE}}^2 - C_{EE}C_{qq}}{np' - C_{qq}}\right) < 0 \tag{45}$$

$$\frac{dp^p}{dE} = \frac{np'C_{qE}}{np' - C_{qq}} < 0 \tag{46}$$

The signs of equations (44)-(46) follow from the assumptions on the cost function and condition (58).

A.1.2 Long Run

In the long run, we need that (38)-(40) and the two following conditions hold

$$pq = C(q, E) + R^pE \tag{47}$$

$$nE = L \tag{48}$$

Furthermore, the second order condition is

$$\mathbf{C_{xx}} = \begin{pmatrix} C_{qq} & C_{Eq} \\ C_{qE} & C_{EE} \end{pmatrix} \quad \text{is positive semidefinite} \tag{49}$$

Differentiating (38)-(40), (47) and (48) totally with respect to L gives

$$\frac{dp}{dL} - C_{qE}\frac{dE}{dL} - C_{qq}\frac{dq}{dL} = 0$$

$$q\frac{dp}{dL} = E\frac{dR}{dL}$$

$$\frac{dR}{dL} = -C_{Eq}\frac{dq}{dL} - C_{EE}\frac{dE}{dL} \tag{50}$$

$$E\frac{dn}{dL} + n\frac{dE}{dL} = 1 \tag{51}$$

$$\frac{dp}{dL} = p'\left(q\frac{dn}{dL} + n\frac{dq}{dL}\right) \tag{52}$$

From these we find the following

$$\frac{dq^p}{dL} = \frac{-qp'\left(EC_{EE} + qC_{qE}\right)}{np'\left(E^2C_{EE} + 2qEC_{qE} + q^2C_{qq}\right) + E^2\left(C_{qE}^2 - C_{EE}C_{qq}\right)} > 0 \tag{53}$$

$$\frac{dE^p}{dL} = \frac{qp'\left(EC_{qE} + qC_{qq}\right)}{np'\left(E^2C_{EE} + 2qEC_{qE} + q^2C_{qq}\right) + E^2\left(C_{qE}^2 - C_{EE}C_{qq}\right)} > 0 \tag{54}$$

$$\frac{dR^p}{dL} = \frac{q^2p'\left({C_{qE}}^2 - C_{EE}C_{qq}\right)}{np'\left(E^2C_{EE} + 2qEC_{qE} + q^2C_{qq}\right) + E^2\left({C_{qE}}^2 - C_{EE}C_{qq}\right)} < 0 \tag{55}$$

$$\frac{dp^p}{dL} = \frac{qEp'\left(C_{qE}^2 - C_{EE}C_{qq}\right)}{np'\left(E^2C_{EE} + 2qEC_{qE} + q^2C_{qq}\right) + E^2\left(C_{qE}^2 - C_{EE}C_{qq}\right)} < 0 \tag{56}$$

$$\frac{dn^p}{dL} = \frac{np'\left(EC_{EE} + qC_{qE}\right) + E\left(C_{qE}^2 - C_{EE}C_{qq}\right)}{np'\left(E^2C_{EE} + 2qEC_{qE} + q^2C_{qq}\right) + E^2\left(C_{qE}^2 - C_{EE}C_{qq}\right)} \tag{57}$$

The signs for the different equations are found through conditions

$$C_{qq}C_{EE} - C_{qE}^2 \geq 0 \tag{58}$$

$$H \equiv q^2C_{qq} + 2qEC_{qE} + E^2C_{EE} \geq 0 \tag{59}$$

$$qC_{qq} + EC_{qE} > 0 \tag{60}$$

$$qC_{qE} + EC_{EE} < 0 \tag{61}$$

Conditions (58) and (59) follow from the second order condition given in (49). The LHS of (58) is the determinant of (49) and must be non-negative. Condition (59) follows from the fact that $\mathbf{h}\mathbf{C_{xx}}\mathbf{h}' \geq 0$ for any vector $\mathbf{h}$. In this case, $\mathbf{h} = (q \quad E)$. Condition (60) is required to guarantee monotonicity with credit trading. By monotonicity we mean that industry emissions should decline when L decreases (see Dijkstra (1999) p. 80 for a discussion). Condition (61) ensures that under credit trading product price decreases with emissions.

It is clear from (59) and (58) that the denominator of (53)-(57) is negative. It can then be easily established that $\frac{dq^p}{dL} > 0$, $\frac{dE^p}{dL} > 0$, $\frac{dR^p}{dL} < 0$ and $\frac{dp^p}{dL} \leq 0$. However, $\frac{dn^p}{dL}$ can either be positive or negative, as the first term in the nominator is positive and the second term is negative. Note however that if $p' = 0$, $\frac{dn^p}{dL} > 0$, implying that as the emissions limit decreases, the number of firms will decrease when demand is infinitely elastic. On the other hand, when $p' \to -\infty$, $\frac{dn^p}{dL} < 0$, implying that when demand is totally inelastic the number of firms will increase when the emission limit decreases.

A.2 Credit Trading

A.2.1 Short Run

For credit trading, the following conditions must hold in the short run

$$p = C_q - R^c \frac{E}{q} \tag{62}$$

$$-C_E = R^c \tag{63}$$

$$p = p(nq) \tag{64}$$

Differentiating these with respect to E gives

$$C_E + E\left(C_{EE} + \frac{dq}{dE}C_{qE}\right) = \frac{E}{q}\frac{dq}{dE}C_E + q\left(\frac{dp}{dE} - C_{qE} - \frac{dq}{dE}C_{qq}\right)$$

and (42) and (43). The solution then is

$$\frac{dq^c}{dE} = \frac{q\left(C_E + EC_{EE} + qC_{qE}\right)}{EC_E + q^2np' - q\left(EC_{qE} + qC_{qq}\right)} > 0 \tag{65}$$

$$\frac{dR^c}{dE} = -\left(\frac{C_E\left(EC_{EE} + qC_{qE}\right) + nq^2p'C_{EE} + q^2\left({C_{qE}}^2 - C_{EE}C_{qq}\right)}{EC_E + q^2np' - q\left(EC_{qE} + qC_{qq}\right)}\right) \tag{66}$$

$$\frac{dp^c}{dE} = \frac{nqp'\left(C_E + EC_{EE} + qC_{qE}\right)}{EC_E + q^2np' - q\left(EC_{qE} + qC_{qq}\right)} < 0 \tag{67}$$

The denominators in (65)-(67) are negative because of (60). The signs of (65) and (67) then follow from (61). The sign of dR^c/dE is ambiguous. However, when going from no regulation (where $C_E = 0$) to regulation, $dR^c/dE < 0$.

Combined Trading For combined trading, the comparative statics change somewhat. Above, we analyzed the effect of a change in total emissions through a change in the emission standard $\bar{e}$. Now, total emissions in the credit sector change through an influx of quotas. As a result, total output in the credit sector rises. Then the emission standard has to be tightened, so that without the extra quotas, total emissions would be equal to the initial industry ceiling M:

$$\bar{e} = \frac{M}{nq} \tag{68}$$

We still need (62)-(64). Differentiating these with respect to E and using (68) gives

$$Mq\left(C_{EE} + q'C_{qE}\right) = Mq'C_E + nq^2\left(p' - C_{qE} - q'C_{qq}\right)$$

and (39) and (40). The solution then is

$$\frac{dq^c}{dL} = \frac{q\left(\bar{e}C_{EE} + C_{qE}\right)}{\bar{e}C_E + qnp' - q\left(\bar{e}C_{qE} + C_{qq}\right)} > 0 \tag{69}$$

$$\frac{dR^c}{dL} = -\left(\frac{\bar{e}C_E C_{EE} + q\left(np'C_{EE} + {C_{qE}}^2 - C_{EE}C_{qq}\right)}{\bar{e}C_E + qnp' - q\left(\bar{e}C_{qE} + C_{qq}\right)}\right) < 0 \tag{70}$$

$$\frac{dp^c}{dL} = \frac{nqp'\left(\bar{e}C_{EE} + C_{qE}\right)}{\bar{e}C_E + qnp' - q\left(\bar{e}C_{qE} + C_{qq}\right)} < 0 \tag{71}$$

The denominators are negative by the fact that $\bar{e} < E/q$ and (60). The signs of (69) and (71) follow from (61) and the sign of (70) follows from (58).

A.2.2 Long Run

In the long run, (62)-(64) and the following conditions must hold

$$pq = C(q, E) \tag{72}$$

$$nE = L \tag{73}$$

The second order condition is given by (49).

Differentiating (62)-(64) and (72)-(73) totally gives

$$-\frac{dp}{dL} + \left(C_{qq} - \frac{E}{q^2}C_E + \frac{E}{q}C_{qE}\right)\frac{dq}{dL} + \left(C_{qE} + \frac{1}{q}C_E + \frac{E}{q}C_{EE}\right)\frac{dE}{dL} = 0$$

$$q\frac{dp}{dL} = C_E\frac{dE}{dL} + C_q\frac{dq}{dL}$$

And (50)-(52).

From these, one can derive the following

$$\frac{dq^c}{dL} = \frac{-q^3 p' \left(E C_{EE} + q C_{qE}\right)}{\left(nq^2 p' + E C_E\right)\left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)} > 0 \tag{74}$$

$$\frac{dE^c}{dL} = \frac{q^3\, p' \, \left(E C_{qE} + q C_{qq}\right)}{\left(nq^2 p' + E C_E\right)\left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)} > 0 \tag{75}$$

$$\frac{dR^c}{dL} = \frac{q^4 p' \left({C_{qE}}^2 - C_{EE} C_{qq}\right)}{\left(nq^2 p' + E C_E\right)\left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)} < 0 \tag{76}$$

$$\frac{dp^c}{dL} = \frac{\left(q\, p'\, C_E\right)\left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)}{\left(n\, q^2\, p' + E\, C_E\right)\left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)} < 0 \tag{77}$$

$$\frac{dn^c}{dL} = \frac{nq^2 p' \left(E C_{EE} + q C_{qE}\right) + C_E \left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)}{\left(nq^2 p' + E C_E\right)\left(E^2 C_{EE} + 2qEC_{qE} + q^2 C_{qq}\right)} \tag{78}$$

Using conditions (58) to (61), it is clear that the denominator of (74)-(78) is negative. It can then be established that $\frac{dq^c}{dL} > 0$, $\frac{dE^c}{dL} > 0$, $\frac{dR}{dL} < 0$ and $\frac{dp^c}{dL} \leq 0$. However, as with permit trading, the sign of $\frac{dn^c}{dL}$ is not immediately clear since the first term in parenthesis in the nominator is negative, while the second term in parenthesis is positive. Hence, the number of firms can both increase or decrease as a result of regulation. However, as with permit trading, $\frac{dn}{dL} > 0$ for $p' = 0$ and $\frac{dn}{dL} < 0$ for $p' \to -\infty$. This implies that when demand is infinitely elastic the number of firms will decrease as the emissions limit decreases and that when demand is totally inelastic the number of firms will increase when the emission limit decreases.

Combined Trading

For the credit sector under combined trading, we still need conditions (62)-(64) and (73) to hold, but the zero-profit condition changes to

$$pq = C(q, E) + R^c(E - \bar{e}q) \tag{79}$$

Furthermore, $\bar{e}$ is now given by (68). Differentiating (62)-(64), (72) and (79) with respect to L, using (68) gives

$$nqM\frac{dR}{dL} = -Mq\frac{dn}{dL}C_E - Mn\frac{dq}{dL}C_E + n^2 q^2 \left(-\frac{dp}{dL} + \frac{dE}{dL}C_{qE} + \frac{dq}{dL}C_{qq}\right)$$

$$-E\left(C_{Eq}\frac{dq}{dL} + C_{EE}\frac{dE}{dL}\right) = q\left(C_{qE}\frac{dE}{dL} + C_{qq}\frac{dq}{dL}\right)$$

And (50)-(52). The solution is

$$\frac{dq}{dL} = -\left(q\, \left(n^2\, q^2\, p' + M\, C_E\right)\, \left(E\, C_{EE} + q\, C_{qE}\right)\right)/D > 0 \tag{80}$$

$$\frac{dE}{dL} = \left(q\,\left(n^2\,q^2\,p' + M\,C_E\right)\,\left(E\,C_{qE} + q\,C_{qq}\right)\right)/D > 0 \tag{81}$$

$$\frac{dR^c}{dL} = \left(q^2\,\left(n^2\,q^2\,p' + M\,C_E\right)\,\left({C_{qE}}^2 - C_{EE}\,C_{qq}\right)\right)/D < 0 \tag{82}$$

$$\frac{dp}{dL} = -\left(nq^3\,\left(M - n\,E\right)\,p'\,\left({C_{qE}}^2 - C_{EE}\,C_{qq}\right)\right)/D < 0 \tag{83}$$

$$\begin{aligned}\frac{dn}{dL} =& \Big[n\,\left(n^2\,q^2\,p' + M\,C_E\right)\,\left(E\,C_{EE} + q\,C_{qE}\right) \\ &+ nq^2\,\left(M - n\,E\right)\,\left(C_{EE}\,C_{qq} - {C_{qE}}^2\right)\Big]/D\end{aligned} \tag{84}$$

Where

$$\begin{aligned}D =& n\left[\left(n^2\,q^2\,p' + MC_E\right)\,\left(E^2\,C_{EE} + 2\,q\,E\,C_{qE} + q^2\,C_{qq}\right)\right. \\ &\left.+ q\,E^2\,(M - n\,E)\,\left(C_{EE}\,C_{qq} - {C_{qE}}^2\right)\right] < 0\end{aligned} \tag{85}$$

To determine the sign of (80)-(85) we need conditions (58)-(61). D is negative from $M < nE$, (58) and (59). dq/dL and dE/dL are positive by (60) and (61). dR/dL and dp/dL are negative by (58) and $M < nE$. The sign of dn/dL is ambiguous.

B Comparative Statics for Imperfect Competition

B.1 Short run

B.1.1 Permit trading

In the short run, the following conditions must hold for permit trading

$$p + p'q = C_q \tag{86}$$
$$-C_E = R \tag{87}$$
$$p = p(nq) \tag{88}$$

For the comparative statics we differentiate (86) to (88) totally with respect to E:

$$\frac{dp}{dE} + p''n\frac{dq}{dE} + p'\frac{dq}{dE} = C_{qq}\frac{dq}{dE} + C_{qE}$$
$$\frac{dR}{dE} = -C_{EE} - C_{qE}\frac{dq}{dE} \tag{89}$$
$$\frac{dp}{dE} = np'\frac{dq}{dE} \tag{90}$$

Defining[2]

$$V \equiv C_{EE}\left(C_{qq} - p''q - 2p'\right) - C_{qE}^2 > 0 \tag{91}$$

$$Z \equiv -\left(qp'' + p'\right) > 0 \tag{92}$$

the solution is:

$$\frac{dq^p}{dE} = \frac{C_{qE}}{(n-1)(qp''+p') + (qp''+2p'-C_{qq})} > 0 \tag{93}$$

$$\frac{dR^p}{dE} = \frac{V + [(n-1)C_{EE}Z]}{(n-1)(qp''+p') + (qp''+2p'-C_{qq})} < 0 \tag{94}$$

$$\frac{dp^p}{dE} = \frac{np'C_{qE}}{(n-1)(qp''+p') + (qp''+2p'-C_{qq})} < 0 \tag{95}$$

The denominators on the RHS are negative by (21) and $C_{qq} > 0$. So in the short run, a tightening of environmental policy leads to lower output, a higher permit price and a higher product price.

B.1.2 Credit trading

In the short run, the following conditions must hold for credit trading

$$p + p'q = C_q - \bar{e}R \tag{96}$$

and (87) and (88).

For the comparative statics, differentiate (96), (87) and (88) totally with respect to E. This gives:

$$\frac{dp}{dE} + qp''n\frac{dq}{dE} + p'\frac{dq}{dE} = C_{qq}\frac{dq}{dE} + C_{qE} + C_E\left(\frac{1}{q} - \frac{E}{q^2}\frac{dq}{dE}\right) + \frac{E}{q}C_{EE} + \frac{E}{q}C_{qE}\frac{dq}{dE}$$

and (89) and (90). The solution is

$$\frac{dq^c}{dE} = \frac{C_E + qC_{qE} + EC_{EE}}{q(nqp''+(n+1)p') + \frac{E}{q}C_E - [qC_{qq} + EC_{qE}]} > 0 \tag{97}$$

$$\frac{dR^c}{dE} = \frac{qV + q(n-1)C_{EE}Z - C_E\left[\frac{E}{q}C_{EE} + C_{qE}\right]}{q(nqp''+(n+1)p') + \frac{E}{q}C_E - [qC_{qq} + EC_{qE}]} \tag{98}$$

$$\frac{dp^c}{dE} = \frac{np'\left[C_E + qC_{qE} + EC_{EE}\right]}{q(nqp''+(n+1)p') + \frac{E}{q}C_E - [qC_{qq} + EC_{qE}]} < 0 \tag{99}$$

with $V > 0$ given by (91) and $Z > 0$ by (92). The denominators are negative by (21) and (60). The numerators are negative in (97) and positive in (99) by (61) and (21). The sign of the numerator in (98) is ambiguous. Note however that when environmental policy goes from non-binding to binding, $C_E = 0$ and (98) is negative. So under credit trading, a tightening of

[2]The inequalities follow from (61) and (21).

environmental policy will lead to lower firm and industry production, while the credit price may increase or decrease. However, initially, when environmental policy becomes binding, the credit price will rise.

B.1.3 Combined Trading

Under combined trading, (87), (88) and (96) still need to hold for the credit sector. However, $\bar{e}$ is now given by $\bar{e} = M/(n^c q^c)$. Differentiating (87), (88) and (96) totally with respect to E gives

$$\frac{dp}{dE} + qp''n\frac{dq}{dE} + p'\frac{dq}{dE} = C_{qq}\frac{dq}{dE} + C_{qE} + \frac{M}{nq^2}C_E\frac{dq}{dE} + \frac{M}{nq}\left(C_{EE} + C_{qE}\frac{dq}{dE}\right)$$

and (89) and (90). The solution is

$$\frac{dq^c}{dE} = \frac{nqC_{qE} + MC_{EE}}{nq\left(nqp'' + (n+1)p'\right) + \frac{M}{q}C_E - \left(nqC_{qq} + MC_{qE}\right)} > 0 \tag{100}$$

$$\frac{dR^c}{dE} = \frac{nqV - nq(n-1)C_{EE}\left(qp'' + p'\right) - \frac{M}{q}C_E C_{EE}}{nq\left(nqp'' + (n+1)p'\right) + \frac{M}{q}C_E - \left(nqC_{qq} + MC_{qE}\right)} < 0 \tag{101}$$

$$\frac{dp^c}{dE} = \frac{np'\left(nqC_{qE} + MC_{EE}\right)}{nq\left(nqp'' + (n+1)p'\right) + \frac{M}{q}C_E - \left(nqC_{qq} + MC_{qE}\right)} < 0 \tag{102}$$

with $V > 0$ given by (91) and $M < nE$. The denominators are negative by (21) and (60). The numerators are positive in (100) and negative in (102) by (61) and (21). The numerator in (101) is negative by (91) and (21).

B.2 Long run

Unlike the case with perfect competition, the number of firms now does not change continuously as environmental policy becomes stricter and stricter. The strictness of environmental policy will affect the firms' profits. If profits decrease, a firm will leave the industry just before profits turn into losses, thereby restoring profitability for the remaining firms. If profits increase, this might attract another firm to the industry, which will reduce profits for each firm. In subsection B.2.1, we will derive the comparative statics for the case where the number of firms remains constant. In subsection B.2.2, we analyze the effects of a change in the number of firms.

B.2.1 Constant number of firms

Permit trading. The comparative statics for permit trading are the same as for the short run. We only need to determine the effect on profits. From (25) and (87), profits can be written as:

$$\pi = pq - C(q, E) + EC_E \tag{103}$$

Then for permit trading, differentiating with respect to E and substituting (86) gives

$$\frac{d\pi}{dE} = q\frac{dP}{dE} - p'q\frac{dq}{dE} + EC_{EE} + EC_{qE}\frac{dq}{dE}$$

Defining:[3]

$$Y \equiv C_{qq}C_{EE} - C_{qE}^2 \geq 0 \tag{104}$$

and substituting (93) and (95) then gives :

$$\frac{d\pi^p}{dE} = \frac{[qC_{qE} + EC_{EE}]\,(n-1)p' - EY + EC_{EE}(np'' + 2p')}{(n-1)(qp'' + p') + (qp'' + 2p' - C_{qq})}$$

The denominator on the RHS is negative by (21). The sign of the numerator is ambiguous, since all terms are positive by (61), (104) and (21).

Thus, the effect of the strictness of environmental policy on profits, and thereby on the entry or exit of firms, is ambiguous.

Credit trading. The first order condition with respect to q now becomes:

$$p + p'q = C_q - \left(\frac{n-1}{n}\right)\bar{e}R \tag{105}$$

The first order condition with respect to E is still (87).

For the comparative statics, differentiate (105), (87) and (88) totally with respect to E:

$$\frac{dp}{dE} + qp''n\frac{dq}{dE} + p'\frac{dq}{dE} =$$
$$= C_{qq}\frac{dq}{dE} + C_{qE} + \left[\frac{n-1}{n}\right]\left[C_E\left(\frac{1}{q} - \frac{E}{q^2}\frac{dq}{dE}\right) + \frac{E}{q}C_{EE} + \frac{E}{q}C_{qE}\frac{dq}{dE}\right]$$

and (89) and (90). Defining:[4]

$$F \equiv q\left((n+1)p' + nqp''\right) + \frac{n-1}{n}\frac{E}{q}C_E - \left[qC_{qq} + \frac{n-1}{n}EC_{qE}\right] < 0 \tag{106}$$

[3]The inequality follows from (58).
[4]The inequality follows from (21) and (60).

the solution is:

$$\begin{aligned}
\frac{dq}{dE} &= \left(\frac{n-1}{n}C_E + \frac{n-1}{n}EC_{EE} + qC_{qE}\right)/F > 0 \qquad (107)\\
\frac{dR}{dE} &= \Big[q\left(C_{EE}\left(C_{qq} - p''q - 2p'\right) - C_{qE}^2\right) + q(n-1)C_{EE}Z \\
&\quad -\frac{n-1}{n}C_E\left(\frac{E}{q}C_{EE} + C_{qE}\right) - 2EC_{EE}C_{qE}\Big]/F \qquad (108)\\
\frac{dp}{dE} &= np'\left[\frac{n-1}{n}C_E + \frac{n-1}{n}EC_{EE} + qC_{qE}\right]/F < 0 \qquad (109)
\end{aligned}$$

with $V > 0$ given by (91) and $Z > 0$ by (92). The numerator is negative in (107) and positive in (109) by (61). The sign of (108) is ambiguous. The result is basically the same as in the short run. A tightening of environmental policy leads to lower firm and industry output, while the credit price may increase or decrease. Note however that when environmental policy is tightened from non-binding to binding, the credit price will increase since in that case $C_E = 0$.

In the long run, profits under credit trading are given by

$$\pi = pq - C(q, E) \qquad (110)$$

Differentiating with respect to E using (105) gives

$$\frac{d\pi}{dE} = q\frac{dp}{dE} + \frac{dq}{dE}\left(\frac{n-1}{n}\frac{E}{q}C_E - p'q\right) - C_E$$

Substituting from (107) and (109) gives

$$\begin{aligned}
\frac{d\pi}{dE} = \Bigg[&\left((n-1)qp' + \frac{n-1}{n}\frac{E}{q}C_E\right) \\
&\left(\frac{n-1}{n}C_E + \frac{n-1}{n}EC_{EE} + qC_{qE}\right) - F\,C_E\Bigg]\Big/F
\end{aligned} \qquad (111)$$

where $F < 0$ is given by (106). The sign of the nominator on the RHS of (111) is ambiguous since the first term is positive by (61) and $-F\,C_E$ is positive. Thus, the effect of the strictness of environmental policy on profits, and thereby on the entry or exit of firms, is ambiguous.

Combined trading. Under combined trading, the comparative statics for the credit sector are somewhat different than the analysis given above for credit trading. Specifically, $\bar{e}$ is now given by $\bar{e} = M/(n^c q^c)$. For the comparative statics we differentiate (105), (87) and (88) totally with respect to E:

$$\begin{aligned}
&\frac{dp}{dE} + \frac{dq}{dE}\left(p' + n\,q\,p''\right) = \\
&\quad C_{qE} + \frac{M}{nq}\left(\frac{n-1}{n}\right)\left[\left(C_{qE} - \frac{1}{q}C_E\right)\frac{dq}{dE} + C_{EE}\right] + \frac{dq}{dE}\,C_{qq}
\end{aligned}$$

and (89) and (90). Defining:[5]

$$S \equiv nq\left(\left(n+1\right)p' + nqp''\right) + \bar{e}\left(n-1\right)C_E - \left(\frac{M}{n}\left(n-1\right)C_{qE} + nqC_{qq}\right) < 0 \tag{112}$$

the solution is:

$$\frac{dq}{dE} = \left[\frac{M}{n}\ (n-1)\ C_{EE} + n\,q\,C_{qE}\right]/S > 0 \tag{113}$$

$$\frac{dR}{dE} = \left[nq\left(C_{EE}\left(C_{qq} - (n+1)p' - nqp''\right) - C_{qE}^2\right) - \bar{e}(n+1)C_E C_{EE}\right]/S < 0 \tag{114}$$

$$\frac{dp}{dE} = n\,p'\left(\frac{M}{n}\ (n-1)\ C_{EE} + n\,q\,C_{qE}\right)/S < 0 \tag{115}$$

The signs of the numerators follow from (61) for (113) and (115) and from (91) for (114).

Differentiating profits in (103) with respect to E, using (105), (113) and (115) gives

$$\begin{aligned}\frac{d\pi}{dE} = \Bigg[& n^2qp'\left(\frac{M}{n}(n-1)C_{EE} + nqC_{qE}\right) + n^2qEC_{EE}\left((n+1)p' + nqp''\right) \\ & + (n-1)\bar{e}C_E\left((n-1)\frac{M}{n}C_{EE} + nqC_{qE}\right) + \bar{e}(n-1)nEC_EC_{EE} \\ & - n^2qEY - p'q\left(M(n-1)C_{EE} + n^2qC_{qE}\right)\Bigg] \Big/ S\end{aligned} \tag{116}$$

where $S < 0$ is given (112). The sign of (116) is ambiguous which follows from (61), (58), (59) and (21).

Therefore, in all cases, it is ambiguous in general whether profits, and by implication the number of firms, increase or decrease as environmental policy is tightened.

B.2.2 A change in the number of firms

Permit trading. Differentiate (86)-(88) totally with respect to n:

$$\frac{dp}{dn} + p''q\left(q + n\frac{dq}{dn}\right) + p'\frac{dq}{dn} = C_{qq}\frac{dq}{dn} - C_{qE}\frac{L}{n^2} \tag{117}$$

$$\frac{dR}{dn} = -C_{qE}\frac{dq}{dn} + C_{EE}\frac{L}{n^2} \tag{118}$$

$$\frac{dp}{dn} = p'\left(q + n\frac{dq}{dn}\right) \tag{119}$$

[5] The inequality follows from (21) and (60).

The solution is:

$$\begin{aligned}\frac{dq^p}{dn} &= \frac{EC_{qE}+nq(p'+qp'')}{nC_{qq}-n(n+1)p'-n^2qp''}<0 && (120)\\ \frac{dR^p}{dn} &= \frac{EV+Z\left[nqC_{qE}+(n-1)EC_{EE}\right]}{nC_{qq}-n(n+1)p'-n^2qp''} && (121)\\ \frac{dp^p}{dn} &= \frac{p'\left[qC_{qq}+EC_{qE}-p'q\right]}{C_{qq}-(n+1)p'-nqp''}<0 && (122)\end{aligned}$$

with $V > 0$ given by (91) and $Z > 0$ by (92). The denominator is positive by (21). The numerators in (120) and (122) are negative by (21). The sign of (121) is ambiguous. So an increase in the number of firms will under permit trading lead to lower firm output, but higher industry output. The permit price may either increase or decrease as a result of the higher number of firms.

To see what happens to profits as n changes, write profits in (103) as

$$\pi = pq - C\left[q, L/n\right] - RL/n \tag{123}$$

and differentiate with respect to n:

$$\frac{d\pi}{dn} = \frac{dp}{dn}q + p\frac{dq}{dn} - C_q\frac{dq}{dn} - \frac{L}{n}\frac{dR}{dn}$$

Substituting (120) to (122) and (86) yields:

$$\begin{aligned}\frac{d\pi^p}{dn} = \Big(& np'H - E^2Y - nq^2p'\left[2p'+qp''\right] + p'E\left[EC_{EE}-qC_{qE}\right] \\ & + nqp''E\left[EC_{EE}+qC_{qE}\right]\Big)\Big/ G\end{aligned} \tag{124}$$

Where

$$G = nC_{qq} - n(n+1)p' - n^2qp''$$

The sign of (124) is ambiguous. Hence, under permit trading, profits may rise or fall with an increase in the number of firms. However, when $p'' \geq 0$, (124) is negative, so that in that case, an increase in the number of firms always leads to a decrease in profits. This is the case given in the simulations and the results given in Tables 7-12 confirm this outcome.

Credit trading. Differentiating (105), (87) and (88) totally with respect to n, we find:

$$\begin{aligned}\frac{dp}{dn} + p''q\left[n\frac{dq}{dn}+q\right] + p'\frac{dq}{dn} &= C_{qq}\frac{dq}{dn} - C_{qE}\frac{L}{n^2} + \frac{1}{n^2}\frac{E}{q}C_E \\ &+ \frac{n-1}{n}\frac{E}{q}\left[-C_E\left(\frac{1}{q}\frac{dq}{dn}+\frac{1}{n}\right) + C_{qE}\frac{dq}{dn} - \frac{E}{n}C_{EE}\right]\end{aligned}$$

and (118) and (119). Define

$$A \equiv nq\left((n+1)p' + nqp''\right) + (n-1)\frac{E}{q}C_E - [nqC_{qq} + (n-1)EC_{qE}] < 0$$

The sign follows from (21) and (60). The solution is:

$$\frac{dq}{dn} = \left(\frac{2-n}{n}EC_E - E\left[qC_{qE} + \frac{n-1}{n}EC_{EE}\right] - nq^2\left[p' + qp''\right]\right)/A \qquad (125)$$

$$\begin{aligned}\frac{dR}{dn} = \Bigg(&-E\,q\,Y + \frac{E}{q}C_E\left[\frac{n-2}{n}qC_{qE} + \frac{n-1}{n}EC_{EE}\right] \\ &-nq(qC_{qE} + EC_{EE})Z + EqC_{EE}p'\Bigg)/A\end{aligned} \qquad (126)$$

$$\frac{dp}{dn} = \left(p'\left[-nH + E\left(qC_{qE} + EC_{EE}\right) + nq^2p' + EC_E\right]\right)/A < 0 \qquad (127)$$

with $Y > 0$ given by (104). The numerator in (127) is positive by (59) and (61). The numerators of (125) and (126) are ambiguous. Hence, as with permit trading, entry leads to higher industry output. However, the effect on firm output and the credit price is ambiguous.

Next, we want to know the effect of a change in the number of firms on profits per firm. Differentiating (110) with respect to n, setting $E = L/n$ gives

$$\frac{d\pi^c}{dn} = q\frac{dp}{dn} + \frac{dq}{dn}\left(\frac{n-1}{n}\frac{E}{q}C_E - p'q\right) + C_E\,\frac{L}{n^2} \qquad (128)$$

Define

$$J \equiv nq\left((n+1)p' + nqp''\right) + (n-1)\frac{E}{q}C_E - [nqC_{qq} + (n-1)EC_{qE}] < 0 \qquad (129)$$

Substituting (125) and (127) in (128) then gives

$$\begin{aligned}\frac{d\pi^c}{dn} = \Bigg\{&qp'\left[E\left(qC_{qE} + EC_{EE}\right) + nq^2p' - nH + EC_E\right] + J\,C_E\,\frac{L}{n^2} \\ &+ \left(\frac{n-1}{n}\frac{E}{q}C_E - p'q\right)\Bigg[[\frac{2-n}{n}EC_E \\ &- E\left(qC_{qE} + \frac{n-1}{n}EC_{EE}\right) - nq^2\left[p' + qp''\right]\Bigg]\Bigg\}/J\end{aligned}$$

The sign of the denominator is ambiguous. Hence, also under credit trading, profits may rise or fall with an increase in the number of firms. This result could imply that an increase in the number of firms will lead to an increase in profits. However, in the simulations given in section 3.2, it can be seen that an increase in the number of firms always leads to a decrease in profits.

Combined Trading. We will not present the comparative statics for combined trading. The reason is that the effect of a change in n on both sectors simultaneously would have to be evaluated. The result then is hard to derive and the outcome is likely to be ambiguous. However, Tables 7 to 12 show that when the number of firms increases, output and emissions per firm decreases, as does the product price and the emissions quota price. For a decrease in the number of firms, we observe the opposite. Note however that in Table 9, when the number of firms in the credit sector drops from 4 to 3, the emissions quota price increases. This is probably caused by the simultaneous increase in emission reductions. However, the simulations also show that an increase in the number of firms always leads to a decrease in profits, while the reverse holds for a decrease in the number of firms.

C The Simulation Model

C.1 Perfect Competition

No Regulation. The situation without regulation is the starting point of the analysis and gives a benchmark for the changes caused by regulation. Without regulation, profits for a firm are given by

$$\pi = pq - aq^2 - b(q-E)^2 - K$$

The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = p - 2aq - 2b(q-E) = 0 \tag{130}$$

$$\frac{\partial \pi}{\partial E} = 2b(q-E) = 0 \quad \Rightarrow \quad q = E \tag{131}$$

Besides these conditions, in the long run there should be no profits:

$$2aq + 2b(q-E) = \frac{aq^2 + b(q-E)^2 + K}{q}$$

Using (131) we find

$$q = \sqrt{\frac{K}{a}}$$

Inserting this in (130) gives:

$$p = 2\sqrt{aK}$$

Denote by $\tilde{n}$ the number of firms without taking the integer constraint into account. Now, $\tilde{n}$ can be found from the inverse demand function given in (37)

$$\tilde{n} = \frac{\alpha\sqrt{\frac{a}{K}} - 2a}{\beta}$$

The equilibrium number of firms is then given by the largest integer less or equal to $\tilde{n}$. Denote the equilibrium values of firm output, product price and number of firms in the no-regulation case by q^0, p^0 and n^0 respectively.

Permit Trading. The initial distribution of permits to incumbent firms is given by

$$\bar{E} = \frac{L}{n^0}$$

The long-run profit maximization problem for the firm is

$$\max_{q,E} \quad \pi = pq - aq^2 - b(q-E)^2 - K - R^p E$$

The first order conditions are given by

$$\frac{\partial \pi}{\partial q} = p - 2aq - 2b(q-E) = 0 \tag{132}$$

$$\frac{\partial \pi}{\partial E} = 2b(q-E) - R^p = 0 \tag{133}$$

Two further condition that need to hold in the long-run equilibrium are

$$nE = L \tag{134}$$

$$2aq + 2b(q-E) = \frac{aq^2 + b(q-E)^2 + K + R^p\, E}{q} \tag{135}$$

Combining equations (132)-(135) gives the following equation for the equilibrium number of firms $\tilde{n}$

$$\frac{b\,L + \sqrt{K\,\tilde{n}^2(a+b) - a\,b\,L^2}}{\tilde{n}\,(a+b)} = \frac{2\,b\,L + \tilde{n}\,\alpha}{\tilde{n}\,\left(2\,a + 2\,b + \tilde{n}\,\beta\right)}$$

The equilibrium $n = n^*$ is then found by rounding down to the nearest integer. Using n^*, q^* can be found through

$$q = \frac{2bL + n\alpha}{n(2a + 2b + n\beta)}$$

After this, the other variables can be found using (37) and (132)-(135).

Credit Trading The relative standard is given by

$$\bar{e} = \frac{L}{nq} = \frac{E}{q}$$

With credit trading, the problem for the firm is

$$\max_{q,E} \quad \pi = pq - aq^2 - b(q-E)^2 - K - R^c(E - \bar{e}q)$$

The first order conditions are

$$\frac{\partial \pi}{\partial q} = p - 2aq - 2b(q-E) + R^c\bar{e} = 0 \tag{136}$$

$$\frac{\partial \pi}{\partial E} = 2b(q - E) - R^c = 0 \quad (137)$$

The other conditions that need to hold are that the industry emission ceiling is met and profits are zero, respectively:

$$nE = L \quad (138)$$

$$2aq + 2b(q - E) - R^c \bar{e} = \frac{aq^2 + b(q - E)^2 + K + R^c(E - \bar{e}q)}{q} \quad (139)$$

In equilibrium, $E = L/n$, and no emissions trading will take place since all firms are identical.

The equilibrium number of firms $\tilde{n}$ can be inferred from

$$\frac{4bL + \tilde{n}\alpha + \sqrt{\tilde{n}\left(\tilde{n}\alpha^2 - 8bL\left(-\alpha + L\beta\right)\right) - 16abL^2}}{2\tilde{n}\left(2a + 2b + \tilde{n}\beta\right)} = \frac{bL + \sqrt{aK\tilde{n}^2(a+b) - abL^2}}{(a+b)\,\tilde{n}}$$

Again, n^* is found by rounding down to the nearest integer. As before, the system can be solved numerically by inserting n^* in the equation for q^*:

$$\frac{4\,b\,L + n\,\alpha + \sqrt{n\,\left(n\,\alpha^2 - 8\,b\,L\,\left(L\,\beta - \alpha\right)\right) - 16\,a\,b\,L^2}}{2\,n\,\left(2\,a + 2\,b + n\,\beta\right)}$$

and then solving for the other variables using equations (136)-(139).

Combined Trading In the case of combined trading, the condition $nE = L$ for both sectors must be replaced by the following two conditions

$$n^c E^c + n^p E^p = 2L \quad (140)$$

$$R^p = R^c = R$$

The first condition merely says that total emissions should be equal to total allowable emissions, while the second condition states that the emission quota prices should be equalized between the two markets.

The number of firms in the permit sector can be found from (132), (133), (135) and (37):

$$\tilde{n}^p = \frac{a\,\left(R^2 - 4\,b\,K\right) + (\alpha - R)\,\sqrt{4ab\left(4\,b\,K - R^2\right)}}{\beta\,\left(4\,b\,K - R^2\right)}$$

For the credit sector, the relative standard is now equal to

$$\bar{e} = \frac{L}{nq} \quad (141)$$

Since trading with the permit sector is allowed, emissions E will in general be different from $\bar{e}q$.

Then, using (136), (137), (139), (141) and (37), we find the following for the number of firms:

$$\tilde{n}^c = \frac{1}{\delta\beta}\Big\{-a(\delta) - (R-\alpha)\sqrt{ab\delta} + \sqrt{a\delta}$$
$$* \sqrt{\left(a\delta + (R-\alpha)\sqrt{4ab\delta} + b\left((R-\alpha)^2 + 4LR\beta\right)\right)}\Big\}$$

where

$$\delta = 4bK - R^2$$

The equilibrium number of firms in both sectors is again found by rounding down. In the simulation model, the number of firms is an integer, and therefore, firm output and emissions need no longer be identical under the two schemes. Firm output and emission are given by

$$q^p = \frac{\alpha - R}{2a + n^p\beta}$$

$$q^c = \frac{n^c(\alpha - R) + \sqrt{(n^c R - n^c\alpha)^2 + 4Ln^c R(2a + n^c\beta)}}{2n^c(2a + n^c\beta)}$$

$$E^p = q^p - \frac{R}{2b}$$

$$E^c = q^c - \frac{R}{2b}$$

The equations for n^p, n^c, E^p, E^c are all functions of R. Inserting these equations in the emissions constraint (140) gives an equation with only R unknown. This can then be solved and used to solve for the other unknowns.

C.2 Imperfect Competition

No Regulation Assuming that all firms are identical, profits are given by:

$$\pi_i = p(Q)q_i - aq_i^2 - b(q_i - E_i)^2 - K$$

where $Q = \sum_{i=1}^{n} q_i$. Using the demand function (37), the first order conditions are:

$$\frac{\partial \pi_i}{\partial q_i} = \alpha - \beta q(n+1) - 2aq_i - 2b(q_i - E_i) = 0$$

$$\frac{\partial \pi_i}{\partial E_i} = 2b(q_i - E_i) = 0 \quad \Rightarrow \quad q_i = E_i$$

In the long run all firms in the market should at least cover their costs, i.e., $\pi_i \geq 0$ and entry should not be profitable. These conditions can be given as:

$$\pi_i(n^0) \geq 0, \quad \text{and} \quad \pi_i(n^0+1) < 0$$

where n^0 is the equilibrium number of firms in the market without regulation. Denote by $\tilde{n}$ the equilibrium number of firms without taking the integer constraint into account. This is given by:

$$\tilde{n} = \frac{-2\,a\,\sqrt{K} - \sqrt{K}\,\beta + \alpha\,\sqrt{a+\beta}}{\sqrt{K}\,\beta}$$

The equilibrium number of firms in the market, n^0, is then given by the greatest integer less than or equal to $\tilde{n}$. The equilibrium output level per firm is given by:

$$q_i^0 = \frac{\alpha}{2a + (1+n^0)\beta}$$

Permit Trading The profit function for the firm becomes:

$$\pi = p(Q)q - aq^2 - b(q-E)^2 - K - R^p(E - \bar{E})$$

The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = \alpha - \beta q(n+1) - 2aq - 2b(q-E) = 0 \tag{142}$$

$$\frac{\partial \pi}{\partial E} = 2b(q-E) - R^p = 0 \tag{143}$$

Since we have assumed that firms are identical, emissions after trading will be $E = L/n$.

Equilibrium output per firm follows from (142)

$$q = \frac{2\,b\,L + n\,\alpha}{n\,\left(2\,a + 2\,b + \beta + n\,\beta\right)} \tag{144}$$

The equilibrium number of firms can be found by solving for q in the zero profit condition and setting it equal to (144)

$$2K = \frac{2bL^2}{\tilde{n}^2} + \frac{\lambda\beta}{\tilde{n}^2\nu^2} + \frac{\mu - \lambda\beta}{\tilde{n}\nu^2} + \frac{\alpha^2\beta(1-\tilde{n}) - \mu}{\nu^2} - \frac{\lambda}{\tilde{n}^2\nu} + \frac{\alpha^2}{\nu} \tag{145}$$

where

$$\lambda = 4b^2L^2, \quad \mu = 4bL\alpha\beta, \quad \text{and} \quad \nu = 2a + 2b + \beta + \tilde{n}\beta$$

The equilibrium number of firms is found by solving (145) for $\tilde{n}$ and rounding down to the nearest integer.

Credit Trading With credit trading, the profits of a firm become:

$$\pi = p(Q)q - aq^2 - b(q-E)^2 - K - R^c E - \bar{e}q)$$

where $\bar{e} = L/Q$. The first order conditions for profit maximization are

$$\frac{\partial \pi}{\partial q} = \alpha - \beta q(n+1) - 2aq - 2b(q-E) + R^c \left(\frac{L}{Q} - q\frac{L}{Q^2} \right) = 0 \tag{146}$$

$$\frac{\partial \pi}{\partial E} = 2b(q-E) - R^c = 0 \tag{147}$$

The equilibrium output can be found from (146)

$$q = \frac{2bLn\,(2n-1) + n^3\alpha + \phi}{2n^3\nu} \tag{148}$$

where

$$\phi \equiv \sqrt{\left(-2bLn + 4bLn^2 + n^3\alpha\right)^2 - 8bL^2\,(-1+n)\,n^3\,(\nu)}$$

The equilibrium number of firms can be be found by solving for q in the zero profit condition and setting it equal to (148)

$$\begin{aligned} 4K = & \frac{\alpha^2}{\nu} - \frac{4bL^2}{\tilde{n}^3} + \frac{\alpha\beta(\alpha - \tilde{n}\alpha - 8bL)}{\nu^2} - \frac{4b^2L^2}{\tilde{n}^4\nu} - \frac{8bL^2\beta}{\tilde{n}^2\nu} + \frac{2bL\phi}{\tilde{n}^5\nu} - \frac{2bL\beta\phi}{\tilde{n}^5\nu^2} \\ & + \frac{2bL\beta(2bL+3\phi)}{\tilde{n}^4\nu^2} + \frac{32b^2L^2\beta - 4bL\alpha\beta - \alpha\beta\phi}{\tilde{n}^2\nu^2} + \frac{4bL\beta(3\alpha - 4bL)}{\tilde{n}\nu^2} \\ & + \frac{4bL(L\beta + \alpha)}{\tilde{n}\nu} + \frac{\alpha\beta\phi - 20b^2L^2\beta - 4bL\beta\phi}{\tilde{n}^3\nu^2} + \frac{\alpha\phi + 8b^2L^2 + 4bL^2\beta}{\tilde{n}^3\nu} \end{aligned}$$

The equilibrium number of firms is found by solving this for $\tilde{n}$ and rounding down to the nearest integer.

Combined Trading Here we need the following conditions

$$2L = n^c E^c + n^p E^p \tag{149}$$

$$R^p = R^c = R$$

For the permit sector we can derive the following equations for output per firm and the number of firms in the permit sector from (144), (143) and the zero profit condition

$$q^p = \frac{-R + \alpha}{2\,a + \beta + n^p\,\beta}$$

$$
\begin{aligned}
&4bK - R^2 + \frac{2b\beta(\tilde{n}^p R^2 + 2R\alpha + \tilde{n}^p \alpha^2)}{\eta^2} + \frac{4bR\alpha}{\eta} \\
= \quad & \frac{2b\beta\left(R^2 + 2\tilde{n}^p R\alpha + \alpha^2\right)}{\eta^2} + \frac{2b(R^2+\alpha^2)}{\eta}
\end{aligned}
$$

where

$$
\eta \equiv 2a + \beta + \tilde{n}^p \beta
$$

This can be solved numerically. The equilibrium number of firms for every emission quota price R is found by rounding the value for $\tilde{n}^p$ down to the nearest integer.

Also under imperfect competition, the relative standard for the credit sector is now given by L/nq. For output per firm in the credit sector, we find from (146) and (147)

$$
q^c = \frac{n^{c2}(\alpha - R) + \sigma}{2n^{c2}\rho} \tag{150}
$$

where

$$
\rho \equiv 2a + \beta + n^c \beta, \quad \sigma \equiv \sqrt{n^{c4}(R-\alpha)^2 + 4L(-1+n^c)\, n^{c2} R(\rho)}
$$

The number of firms in the credit sector can be derived from (150) and the zero profit condition

$$
\begin{aligned}
&4bK - R^2 + \frac{b\beta(n^c R^2 + 2R\alpha + n^c\alpha^2)}{\rho^2} + \frac{2bR(\alpha + L\beta)}{\rho} \\
&+ \frac{bR(\sigma + 2L\beta) - b\alpha\sigma}{n^{c2}\rho} + \frac{b\beta\sigma(R-\alpha)}{n^{c2}\rho^2} - \frac{2bLR}{n^{c2}} - \frac{2bLR}{n^c} \\
= \quad & \frac{b\beta(R^2 + 2n^c R\alpha + \alpha^2)}{\rho^2} + \frac{b(R^2+\alpha^2)}{\rho} + \frac{4bLR\beta}{n^c\rho} + \frac{b\beta\sigma(R-\alpha)}{n^c\rho^2}
\end{aligned}
$$

Using these equations and the first order condition for emissions, we can derive equations for n^p, E^p, n^c, and E^c that are only functions of R. However, because the number of firms in each sector is an integer, and the expressions above give a rational number, we cannot derive an expression for the equilibrium value of R. Instead, the equilibrium value of R was found through iteration, where the starting value of the iteration was R^p for every case and a small amount was added until the equilibrium value was found.

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