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Emissions Trading and Intersectoral Dynamics: Absolute versus Relative Design Schemes

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Abstract

This paper examines the interdependence between imperfect competition and emissions trading in a two-sector (clean and dirty) economy. We compare the welfare implications of an *absolute* cap-and-trade scheme (permit trading) with a *relative* intensity-based scheme (credit trading). We find unambiguously more clean firms in the long run under credit trading. However, neither emissions trading configuration creates the first-best outcome: there are too few (many) clean firms under permit (credit) trading. Permit trading dominates credit trading in terms of overall welfare at the long run equilibrium, except when policy is relatively lenient. It is also demonstrated that stricter policy does not necessarily induce the clean sector to grow relative to the dirty sector and we determine under what conditions this holds.

Keywords: emissions trading, imperfect competition, industrial change, pollution control, sectoral dynamics

JEL classification: D62, Q48, Q52, Q58

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1 Introduction

Worldwide, governmental authorities increasingly embark upon trading schemes to efficiently curtail environmental pollution. This paper analyzes and compares the two main market configurations for organizing trade in emission allowances: cap-and-trade versus intensity-based trading. Although tradable pollution markets have been studied extensively in recent years, a systematic comparison between these pollution market designs in an imperfectly competitive multi-sector model is still lacking. The aim of this paper is to fill this gap. Since polluting industries are often concentrated in nature, we allow firms to strategically interact in an imperfectly competitive output market and assess the sectoral implications of these policies in the long run equilibrium. The specific question we address in this paper is to what extent permit and credit trading schemes impact on the intersectoral out-of-equilibrium dynamics ("clean" vs. "dirty") in the short run and the corresponding equilibrium in the long run. Analyzing the interaction between emissions trading and output market effects is an important dimension in policy assessments, since it is often not optimal to completely eliminate the pollution intensive (dirty) sector, even though reducing pollution is the underlying policy goal.

Cap-and-trade (permit trading hereafter) and intensity-based emissions trading (credit trading hereafter) represent schemes that are based on an *absolute* cap on emissions and on *relative* emission intensities, respectively.[1] Whereas under permit trading the control authority fixes the *total* supply of emissions, in case of credit trading the authority imposes a source-specific level of emissions abatement, implying a fixed *average* emissions intensity (e.g., Tietenberg, 1999). Prime examples of permit trading schemes in the U.S. are the acid rain programme, which started in 1995, and the RECLAIM programme to cut back sulfur dioxide and nitrogen oxide emissions from stationary sources in the Los Angeles basin implemented in 1994. The European counterpart of large scale permit trading currently occurs within the European Union Emission Trading System (EU ETS) for carbon dioxide emissions. In the 1980s, U.S. policy also experimented with credit trading arrangements between refineries as part of the lead phasedown (see, e.g., Hahn and Hester, 1989).[2] In Canada a credit trading system was launched in 1996 under the Pilot Emission Reduction Target and is currently one of the main design features of Canada's climate policy (Environment Canada, 2007). Also for developing countries intensity targets have been suggested (e.g., Philibert and Pershing, 2001; Michaelowa, 2005), which will likely be one of the subjects in the upcoming post-Kyoto emissions trading design debate.

We show that (strategic) competition in the output market is a prime factor in the interplay between sectoral choice, production and emissions trading. The interaction in the output and permit market in the short run, and the corresponding sectoral equilibrium distribution

[1] Different labels are used in the literature for the two schemes. Cap-and-trade schemes are also referred to as allowance or permit trading; intensity-based schemes are also called credit trading, tradable performance standards or rate-based trading. See Stavins (2003) for an extensive account of various programmes.

[2] Kerr and Newell (2003) empirically assess the performance of credit trading in the U.S. lead phase down programme and found that this type of allowance trading provided significant incentives for refineries to adopt cost-effective technologies.

in the long run, is analyzed and compared such that the total long run level of emissions under both schemes is the same. The latter ensures a fair comparison of the two schemes and at the same time makes the analysis more tractable.

Four main insights emerge from our analysis. First, in the long run, credit trading unambiguously provides a greater proportion of clean firms compared to permit trading for *all* binding pollution targets. Second, the long run equilibrium proportion of firms in the clean sector is suboptimal under both emissions trading schemes: the share of clean firms is typically too high under credit trading, whereas permit trading results in too few clean firms. Third, permit trading generally dominates credit trading in terms of overall welfare in the long run, except for the case when policy is relatively lenient. Fourth, although more stringent environmental policy is often a driver behind an expansion of clean output relative to dirty output, we show that the relative growth of the clean sector in the economy is not guaranteed under permit trading when the cap on emissions is tightened. Indeed, it may not even be optimal for the clean sector to grow relative to the dirty sector.

Previous studies that compare emissions trading on the basis of absolute and relative targets with each other have ignored the multi-sectoral implications under imperfect competition. Dewees (2001) makes a welfare comparison between the two emissions trading schemes in a single perfectly competitive industry, whereas Boom and Dijkstra (2009) make the comparison for a perfectly as well as an imperfectly competitive sector. Fischer (2003) analyzes emission trading between two perfectly competitive sectors, one of them regulated by a permit scheme and the other by a credit scheme. Boom and Dijkstra (2009) analyze the same scenario for two perfectly competitive and two imperfectly competitive sectors.

The paper proceeds as follows. In the next section we introduce the model. Section 3 discusses how emissions trading affects the sectoral output mix in the short run. Given the output and profit dynamics in the short run, Section 4 turns to a discussion of the long run equilibria under the two emissions trading schemes. In Section 5 we derive the long run welfare optima and compare the welfare effects of permit and credit trading. Concluding remarks are given in Section 6.

2 The model

Below we first present the basic model (Section 2.1). Then we present the unconstrained benchmark, reflecting the long run equilibrium without environmental policy (Section 2.2). This is followed by the formalization and functioning of the two emissions trading schemes (Section 2.3). We conclude with the derivation of the short run equilibria in both the output and pollution market (Section 2.4).

2.1 Basic elements

Consider two imperfectly competitive markets consisting of a total of $n \geq 2$ firms that choose output to maximize profit. Each firm faces two decisions: (1) a long run decision between producing in the clean sector ($i = c$) or the dirty sector ($i = d$), and (2) the short run output decision given the choice of sector. Each firm $f = 1, \ldots, n$ chooses output, taking as given the number of firms in each sector. Given the sector in which a firm is operating, firm-level emissions $e_i > 0$ are assumed to vary proportionally with firm-level output $q_i > 0$ for both goods:

$$e_i = \epsilon_i q_i. \qquad i = c, d. \tag{1}$$

By definition, emissions per unit of output are lower for the clean good, i.e., $\epsilon_c < \epsilon_d$.

Define the variable $s \in [0, 1]$ as the fraction of firms in the clean sector. The number of clean firms n_c and dirty firms n_d is then given by:

$$n_c \equiv sn \qquad\qquad n_d \equiv (1 - s)n. \tag{2}$$

Aggregate output produced by firms in the clean and dirty sector is simply $Q_i = n_i q_i$ $(i = c, d)$. The two sectors face the following inverse demand functions:

$$p_i = \alpha_i - Q_i, \qquad i = c, d \tag{3}$$

where p_i is the price of good i and Q_i is the aggregate output supplied by the firms that compete in sector i. A higher α_i (relative to α_{-i}) implies an absolute advantage in demand (at equal output levels) enjoyed by the firm in sector i (e.g., Dixit, 1979). Put differently, $\alpha_i - \alpha_{-i}$ reflects a price premium for sector i.

Fixed costs are normalized to zero since they do not affect the output decision at the margin.[3] Both sectors exhibit constant returns to scale (i.e., they are linearly homogenous), implying constant marginal cost $c_i > 0$. Total production costs C_i are then proportional to output:

$$C_i = c_i q_i, \qquad i = c, d \tag{4}$$

Following Dixit (1979), the cost margin for a firm in sector i is defined as $\theta_i \equiv \alpha_i - c_i > 0$, and a firm in sector i has a margin advantage if $\theta_i > \theta_{-i}$.

2.2 The unconstrained benchmark

We first determine the *unconstrained* benchmark, i.e., the long run equilibrium without environmental policy. In this case the firm's profit (π_i) maximization problem is simply:

$$\max_{q_i} \pi_i = (p_i - c_i)q_i, \qquad i = c, d. \tag{5}$$

The unconstrained Cournot-Nash quantities are then accordingly:

$$\bar{q}_i(s) = \frac{\theta_i}{n_i(s) + 1} \qquad i = c, d, \tag{6}$$

with $n_i(s)$ given by (2). Given linear demand and constant marginal cost, profits can be written as:

$$\bar{\pi}_i(s) = [\bar{q}_i(s)]^2 = \left[\frac{\theta_i}{n_i(s) + 1}\right]^2 \qquad i = c, d. \tag{7}$$

[3] Positive but homogeneous fixed costs for the different sectors do not affect the model, other than reducing profit levels. Heterogeneous fixed costs shift the long run equilibrium towards the sector with the lower fixed cost, but otherwise the results are qualitatively unchanged.

In the unconstrained equilibrium firms are indifferent between the two sectors in terms of profitability, so that $\bar{\pi}_c(s) = \bar{\pi}_d(s)$. From (7) this directly implies that $\bar{q}_d(s) = \bar{q}_c(s)$. Using (6), solving this equality for s yields the following unconstrained equilibrium:

$$\bar{s}^* = \frac{\theta_c(n+1) - \theta_d}{n(\theta_c + \theta_d)}. \tag{8}$$

An unconstrained interior equilibrium $0 < \bar{s}^* < 1$, is obtained for all parameters such that:

$$\frac{\theta_d}{n+1} < \theta_c < \theta_d(n+1). \tag{9}$$

When (9) holds there are firms in both the clean and dirty sectors, even in the absence of environmental policy. Substituting (8) into (6), the Cournot-Nash quantities at the unconstrained equilibrium read:

$$\bar{q}_c^* = \bar{q}_d^* = \bar{q}^* \equiv \frac{\theta_c + \theta_d}{n+2}. \tag{10}$$

Next we examine how firms respond to a change in production costs, which can be brought about by environmental policy (to be discussed in Section 3). Using (6), in the unconstrained equilibrium $\bar{s}^*$, the response of a firm in sector i to a change in production costs c_i is:

$$\frac{d\bar{q}_i}{dc_i} = -\frac{d\bar{q}_i}{d\theta_i} = -\frac{1}{n_i(\bar{s}^*)+1} = -\frac{\bar{q}^*}{\theta_i}, \tag{11}$$

with $\bar{q}^*$ given by (10). For illustration, suppose that $\theta_i > \theta_{-i}$, that is sector i has a margin advantage over sector $-i$. Then the reduction in output (and hence profit) for a firm in sector i is smallest. This is because in the unconstrained equilibrium there are more firms in sector i than in sector $-i$, as is clear from setting $\bar{q}_c = \bar{q}_d$ in (6). An increase in the marginal cost, c_i, will prompt a firm in sector i to reduce its output, but this reduction is cushioned by the fact that all the other competitors also reduce output, thereby raising the output price. In sector $-i$ the competitive pressure is less due to fewer number of firms, which provides each firm with less of a cushion and forces it to cut back output further.

As we shall see more formally in Section 3, at any long run equilibrium with profits equalized across sectors it holds that $q_c^* = q_d^* = q^*$, so that aggregate emissions are:

$$E^* = \epsilon_c s^* n q_c^* + \epsilon_d(1-s^*) n q_d^* = n\left(\epsilon_c s^* + \epsilon_d(1-s^*)\right) q^*. \tag{12}$$

Substituting (8) and (10), aggregate emissions in the unconstrained benchmark are:

$$\bar{E}^* = \frac{n\left(\epsilon_c\theta_c + \epsilon_d\theta_d\right) + \left(\theta_d - \theta_c\right)\left(\epsilon_d - \epsilon_c\right)}{n+2}. \tag{13}$$

2.3 Formalizing emissions trading

Considering the two distinguished emissions trading schemes, denote emissions trading on the basis of an *absolute* cap on aggregate pollution by A and emissions trading on the basis of pollution *intensities* by I. As stated earlier, we refer to the former as permit trading and the latter as credit trading in what follows.

Given an absolute cap, L, under permit trading, firms sell (buy) permits when their emissions e_i are less than (exceed) their permit endowment, $\bar{e}_i$. Permits are sold at price v and the firm's profit maximization problem in sector i is:

$$\max_{e_i} \pi_{iA} = (p_i - c_i)q_i + v\left(\bar{e}_i - e_i\right) \qquad i = c, d. \tag{14}$$

The cap is non-binding if it is greater or equal to the unconstrained level of emissions given by equation (13), i.e., $L \geq \bar{E}^*$. A non-binding cap on pollution will result in a permit price $v = 0$. A cap $L < \bar{E}^*$ is binding with a permit price $v > 0$, ensuring that the demand for permits is equal to its supply:

$$\sum_{i=c,d} \epsilon_i n_i q_i = L \qquad i = c, d. \tag{15}$$

When firms move from the dirty to the clean sector, aggregate clean sector output $Q_c = n_c q_c$ rises and permit demand by the clean sector increases. This induces the permit price to go up causing total dirty sector output Q_d and permit demand by the dirty sector to fall, so that total permit demand again equals the fixed supply L.

In contrast to a permit system, under a tradable credit scheme the government sets an economy-wide pollution intensity standard, denoted δ. If a firm wants to emit more than the standard allows, it can buy credits from firms that emit less than the standard allows. Thus, clean firms always sell, and dirty firms always buy credits. The result is that *on average* the economy as a whole complies with the emission standard but the individual firm has the flexibility to deviate from it. Alternatively, the emission standard can be seen as a weighted average of the emission intensities:

$$\delta = x\epsilon_c + (1 - x)\epsilon_d \qquad \bar{s}^* \leq x \leq 1. \tag{16}$$

From (12) and (16) it is clear that $x = s^*$ in the long run equilibrium, i.e., the equilibrium proportion of clean firms always coincides with the weighted average of the sectors' emission intensities. A weighted average x at or below the unconstrained level $\bar{s}^*$, given in (8), is non-binding and will result in a credit price $w = 0$; a weighted average $x > \bar{s}^*$ is binding and will result in $w > 0$. The upper-bound weight $x = 1$ implies a policy where the standard solely reflects the emissions intensity of the clean sector. Setting $x = 1$ implies $\delta = \epsilon_c$, hence inducing the elimination of the dirty sector.

Under the credit trading scheme a firm's profit maximization problem is:

$$\max_{e_i} \pi_{iI} = (p_i - c_i)q_i + w\left(\delta q_i - e_i\right) \qquad i = c, d \tag{17}$$

and the credit market clears via the constraint:

$$n_d q_d(\delta - \epsilon_d) = n_c q_c(\epsilon_c - \delta). \tag{18}$$

This constraint reveals the key difference in the functioning of the permit and credit market. Whereas the supply of allowances (L) is fixed under the permit regime, the supply of credits

— the RHS of (18) — varies with aggregate clean output $Q_c = n_c q_c$. When firms move from the dirty to the clean sector (n_d declines and n_c rises) and $Q_c = n_c q_c$ rises, the supply of credits from firms in the clean sector increases. This results in a fall of the credit price so that total production Q_d and credit demand by firms in the dirty sector rises. In contrast, when aggregate output of the clean sector Q_c rises under permit trading, the permit price also rises and aggregate output of the dirty sector Q_d falls.

Note that while we consider imperfect competition in the output market, it is assumed that firms act as price takers in the emissions market. Although this may seem restrictive, it is, however, a credible assumption and not in conflict with the imperfectly competitive nature of the output market. For instance, the EU ETS for carbon emissions allows trade between power generating firms, steel producers, glass manufacturers as well as firms from the paper and cement industry. As a consequence, the pollution market can be competitive while competition in the respective output markets is imperfect.

2.4 Short run equilibrium in the output and pollution market

In the short run a firm's choice of sector is given under each trading scheme. We can then solve the firm's profit maximization optimization problems (14) and (17) as follows. Substituting (1) and (3) into the profit function (14) under permit trading, the first-order condition for a firm in sector i is (derivation in Appendix):

$$\frac{1}{\epsilon_i}\left[\theta_i - \frac{e_i(n_i+1)}{\epsilon_i}\right] = v(s,L) \qquad i = c, d. \tag{19}$$

The LHS of (19) is the marginal revenue per unit of pollution and the RHS is the marginal cost, i.e., permit price. The optimal short run Cournot-Nash equilibrium output levels are:

$$q_i(s,L) = \frac{\theta_i - \epsilon_i v(s,L)}{n_i(s)+1} \qquad i = c, d. \tag{20}$$

Using (20), firm profit under the permit trading scheme simplifies to (see Appendix):

$$\pi_{iA}(s,L) = [q_{iA}(s,L)]^2 + v\bar{e}_i = \left[\frac{\theta_i - \epsilon_i v(s,L)}{n_i+1}\right]^2 + v\bar{e}_i. \tag{21}$$

There is a given distribution of clean and dirty firms, thus s is fixed in the short run. The equilibrium permit price v is obtained by substituting (20) into (15), yielding:

$$v(s,L) = \frac{ns\theta_c\epsilon_c\left[n\left(1-s\right)+1\right] + n\theta_d\epsilon_d\left(ns+1\right)\left(1-s\right) - L\left[s\left(1-s\right)n^2+n+1\right]}{ns\left(n\left(1-s\right)+1\right)\epsilon_c^2 + n\left(ns+1\right)\left(1-s\right)\epsilon_d^2}. \tag{22}$$

Substituting (22) into (20) generates the following short run equilibrium output level

$$q_{iA}(s,L) = \frac{L\epsilon_i\left(1+n_{-i}\right) + n_{-i}\epsilon_{-i}\left(\theta_i\epsilon_{-i} - \theta_{-i}\epsilon_i\right)}{n_i\left(n_{-i}+1\right)\epsilon_i^2 + n_{-i}\left(n_i+1\right)\epsilon_{-i}^2}.$$

Similarly for the credit trading scheme, substitution of (1) and (3) into the profit function (17) yields the following first-order condition of a firm in sector $i = c, d$ (derivation in Appendix):

$$\frac{1}{\epsilon_i}\left[\theta_i - \frac{e_i\left(n_i+1\right)}{\epsilon_i}\right] = -\frac{w(\delta - \epsilon_i)}{\epsilon_i} \qquad i = c, d, \tag{23}$$

which yields Cournot-Nash outputs:

$$q_{iI}(s,\delta) = \frac{\theta_i + w(\delta - \epsilon_i)}{n_i + 1} \qquad i = c, d. \tag{24}$$

Firm-level profit under the credit scheme then becomes (see Appendix):

$$\pi_{iI}(s,\delta) = [q_{iI}(s,\delta)]^2 = \left[\frac{\theta_i + (\delta - \epsilon_i)w(s,\delta)}{n_i + 1}\right]^2. \tag{25}$$

The corresponding price for tradable credits is found by substituting (24) into the credit market equilibrium condition (18), yielding:

$$w(s,\delta) = \frac{s\theta_c(n_d+1)(\epsilon_c - \delta) + (1-s)\theta_d(n_c+1)(\epsilon_d - \delta)}{s(n_d+1)(\epsilon_c-\delta)^2 + (1-s)(n_c+1)(\epsilon_d-\delta)^2}. \tag{26}$$

Substituting (26) into (24) one obtains:

$$q_c(s,\delta) = n_d(\epsilon_d - \delta)\Theta, \qquad q_d(s,\delta) = n_c(\delta - \epsilon_c)\Theta, \tag{27}$$

where $\Theta \equiv \frac{\theta_d(\epsilon_c-\delta)+\theta_c(\delta-\epsilon_d)}{n_c(n_d+1)(\epsilon_c-\delta)^2+n_d(n_c+1)(\epsilon_d-\delta)^2} > 0$, implying q_c and q_d are always positive under credit trading.

By building upon the short run output quantities, in the next section we will concentrate on the sectoral dynamics and examine the emissions trading properties under both schemes. Once this platform is established we can determine and assess the long run equilibrium outcome.

3 Sectoral dynamics and emissions trading

In the long run equilibrium, not only are the output and pollution market in equilibrium but firms are also indifferent switching between producing in the clean and the dirty sector. We introduce environmental policy at the unconstrained equilibrium, as described in subsection 2.2. The strictness of environmental policy — the cap L under permit trading and the emission standard δ under credit trading — is set at its long run target. Firms adjust their output levels immediately, but only gradually start moving toward the sector that would yield them higher profits. This gradual adjustment process continues until profits are equated across sectors in the long run equilibrium.[4] We will now provide some comparative statics for the emissions trading mechanism in relation to this adjustment process under both types of trading schemes.

Permit trading, with a total of L permits issued, is introduced in the unconstrained equilibrium with $s = \bar{s}^*$ given by (8) and $\bar{q}_c^* = \bar{q}_d^* = \bar{q}^*$ given by (10). Combining these with (20), we can write output under permit trading at $s = \bar{s}^*$ as:

$$q_i(\bar{s}^*, L) = \bar{q}^* \left[1 - \frac{\epsilon_i}{\theta_i} v(\bar{s}^*, L)\right],$$

[4] See, e.g., Witt (1997) for a general justification of such an adjustment process.

and we see that

$$\frac{\partial q_i(\bar{s}^*, L)}{\partial v} = \epsilon_i \frac{d\bar{q}_i}{dc_i} = -\frac{\bar{q}^*}{\phi_i} \equiv -\frac{\epsilon_i \bar{q}^*}{\theta_i}.$$

The permit price v translates into production costs of $\epsilon_i v$. Thus, a marginal increase in v has the same effect as ϵ_i times an increase in the marginal cost, c_i. We know from (11) that the reduction in output q_i due to an increase in c_i is inversely related to a firm's cost margin advantage on output, θ_i. That is, a rising permit price reduces output and profit in both sectors but less so in the sector with the highest θ_i/ϵ_i ratio. While θ_i is the cost margin on output, we call $\phi_i \equiv \theta_i/\epsilon_i$ the cost margin on emissions.

Starting from the unconstrained equilibrium, firms will start moving to the sector with the highest cost margin on emissions where, by (21), output per firm and profit is higher. Note, however, that environmental policy in the form of permit trading does not necessarily lead to more clean firms. It only induces more clean firms if θ_c is larger (or not too much smaller) than θ_d. However, for $\theta_c << \theta_d$ we have $\phi_d > \phi_c$, implying firms move from the clean to the dirty sector. From (22), the sign of the permit price change over time is the sign of:

$$\frac{\partial v(s, L)/\partial s}{\phi_c - \phi_d} = \frac{n\epsilon_c^2 \epsilon_d^2 (n + 1 - 2ns(1 - s)) - b(s)L}{n \left[s\left(n\left(1 - s\right) + 1\right)\epsilon_c^2 + \left(ns + 1\right)\left(1 - s\right)\epsilon_d^2\right]^2}. \tag{28}$$

The first term in the numerator on the RHS is positive. The second term is also positive with $b(s) \equiv \frac{(ns+1)^2\epsilon_d^2 - (n(1-s)+1)^2\epsilon_c^2}{\phi_c - \phi_d} > 0$ and increasing over time. In the unconstrained equilibrium benchmark we obtain

$$b(\bar{s}^*) = (\phi_c + \phi_d)\left[\frac{\epsilon_c \epsilon_d \left(n + 2\right)}{\theta_c + \theta_d}\right]^2. \tag{29}$$

Approaching the new long-run equilibrium with s_A^* clean firms, as given in Table 1, we find from (28) that:

$$\frac{\partial v(s_A^*, L)/\partial s}{\phi_c - \phi_d} = -\frac{\epsilon_c \epsilon_d}{n \left[\left(n\left[1 - s\right] + 1\right) s\epsilon_c^2 + \left(ns + 1\right)\left(1 - s\right)\epsilon_d^2\right]^2} < 0. \tag{30}$$

Thus the permit price will be declining in the end, toward the new equilibrium. This means that towards the end, the second term in the numerator on the RHS of (28) dominates the first term. With the second term increasing over time along with $b(s)$, the permit price will initially be decreasing over time when L is large and increasing when L is small.

Next, let us turn to credit trading. The emission standard δ is introduced at the unconstrained equilibrium with $s = \bar{s}^*$ given by (8) and $\bar{q}_c^* = \bar{q}_d^* = \bar{q}^*$ given by (10). Combining these equations with (24) we can write output under credit trading at $s = \bar{s}^*$ as:

$$q_i(\bar{s}^*, \delta) = \bar{q}^* \left[1 + \frac{w(\delta - \epsilon_i)}{\theta_i}\right] \qquad i = c, d.$$

As a result of the imposed policy, producing an extra unit of dirty output now carries an extra cost of $w(\delta - \epsilon_d)$, i.e., an extra unit of production yields δ extra credits but ϵ_d extra pollution. Thus, the firm is $\delta - \epsilon_d$ credits short, which it has to buy at price w. Conversely, production of the clean good is "subsidized" at rate $w(\delta - \epsilon_c)$, because extra production yields more credits than the clean firm needs. This implies that under a credit trading regime the production of the clean good rises above the unconstrained equilibrium level $\bar{q}^*$ and production of the dirty good falls below it.

Starting from the unconstrained equilibrium, firms will start moving to the clean sector where output per firm and profits are higher, by (25). As expected, as the number of clean firms increases over time, we see from (26) that the credit price decreases:

$$\frac{\partial w(s,\delta)}{\partial s} = \frac{-\left[n - 2s(1-s)n + 1\right](\delta - \epsilon_c)(\epsilon_d - \delta)[\theta_c(\epsilon_d - \delta) + \theta_d(\delta - \epsilon_c)]}{\left[s((1-s)n+1)(\delta-\epsilon_c)^2 + (1-s)(sn+1)(\delta-\epsilon_d)^2\right]^2} < 0, \qquad (31)$$

while from equation (24) the changes in dirty and clean production per firm are given by:[5]

$$\frac{\partial q_i(s,\delta)}{\partial s} = \frac{\frac{\partial w}{\partial s}(\delta - \epsilon_i)(n_i+1) - \frac{dn_i}{ds}\left[\theta_i + w(\delta - \epsilon_i)\right]}{(n_i+1)^2} \qquad i = c, d.$$

The firm's adjustment unfolds as explained in Section 2.3 following (18). As more and more firms switch to the clean sector (s increases), the supply of credits by clean firms rises [the RHS of (18)]. This depresses the credit price ($\partial w/\partial s < 0$), allowing the remaining firms in the dirty sector to increase their output ($\partial q_d/\partial s > 0$) and their demand for credits [the LHS of (18)]. Finally, output per clean firm decreases ($\partial q_c/\partial s < 0$) both because firms enter the clean sector and because the credit price falls.

Recall that at the unconstrained equilibrium $\bar{s}^*$ (our point of departure) the output level per firm and profit is higher in the clean sector once regulation in the form of emissions trading is imposed. This attracts firms to the clean sector, which in turn reduces output per firm and profit in this sector. Profit in the dirty sector increases as firms exit the dirty sector and enter the clean sector. This process reduces the profit differential as more firms switch to the clean sector until profit is equated in the long run equilibrium. Now that we understand the functioning behind the intersectoral adjustment dynamics, we will make the step towards examining the corresponding long run equilibrium under the two emissions trading schemes in greater detail.

4 Long run equilibrium

In the long run equilibrium firms have no incentive to switch sectors since all firms earn the same profit, i.e., $\pi_{ck} = \pi_{dk}$ ($k = A, I$). Given profits as expressed by (21) and (25), one can straightforwardly solve $\pi_c = \pi_d$ for s under both trading schemes, yielding the long run equilibrium proportion s_k^* of firms in the clean sector. Table 1 contains these long run equilibria for both emissions trading schemes as well as the associated equilibrium values of other key variables.

4.1 Reaching a target level of emissions under permit and credit trading

Suppose the regulator wishes to achieve a certain level of emissions $E^* = E_A^* = E_I^*$ in the long run equilibrium. Under permit trading the regulator can simply issue a total number

[5] We know from (31) that $\partial w/\partial s < 0$ and from (24) and (27) that $\theta_i + w(\delta - \epsilon_i) > 0$ for $i = c, d$. Then $\partial q_c/\partial s < 0$ because $\delta - \epsilon_c < 0$ and $dn_c/ds = n > 0$, while $\partial q_d/\partial s > 0$ because $\delta - \epsilon_d < 0$ and $dn_d/ds = -n < 0$.

Table 1: Long run equilibrium values

	Permit trading	Credit trading
Clean sector size	$s_A^* = \frac{n\epsilon_d[\theta_c\epsilon_d-\theta_d\epsilon_c]+L[\epsilon_c(n+1)-\epsilon_d]}{n[(\theta_c\epsilon_d-\theta_d\epsilon_c)(\epsilon_d-\epsilon_c)+L(\epsilon_c+\epsilon_d)]}$	$s_I^* = \frac{\epsilon_d-\delta}{\epsilon_d-\epsilon_c} = x$
Firm output	$q_c^* = q_d^* = \frac{\theta_c\epsilon_d(\epsilon_d-\epsilon_c)-\theta_d\epsilon_c(\epsilon_d-\epsilon_c)+L(\epsilon_d+\epsilon_c)}{n(\epsilon_c^2+\epsilon_d^2)+(\epsilon_d-\epsilon_c)^2}$	$q_c^* = q_d^* = \frac{x\theta_c+(1-x)\theta_d}{2nx(x-1)+n+1}$
Agg. clean output	$Q_c^* = \frac{n\epsilon_d[\theta_c\epsilon_d-\theta_d\epsilon_c]+L[\epsilon_c(n+1)-\epsilon_d]}{n(\epsilon_c^2+\epsilon_d^2)+(\epsilon_d-\epsilon_c)^2}$	$Q_c^* = \frac{nx[x\theta_c+(1-x)\theta_d]}{2nx(x-1)+n+1}$
Agg. dirty output	$Q_d^* = \frac{n\epsilon_c[\theta_d\epsilon_c-\theta_c\epsilon_d]+L[\epsilon_d(n+1)-\epsilon_c]}{n(\epsilon_c^2+\epsilon_d^2)+(\epsilon_d-\epsilon_c)^2}$	$Q_d^* = \frac{n(1-x)[x\theta_c+(1-x)\theta_d]}{2nx(x-1)+n+1}$
Allowance price	$v^* = \frac{\theta_c[\epsilon_c(n+1)-\epsilon_d]+\theta_d[\epsilon_d(n+1)-\epsilon_c]-L(n+2)}{n(\epsilon_c^2+\epsilon_d^2)+(\epsilon_d-\epsilon_c)^2}$	$w^* = \frac{\theta_d(nx+1)-\theta_c[n(1-x)+1]}{(\epsilon_d-\epsilon_c)(2nx(x-1)+n+1)}$
Emissions	$E_A^* = L$	$E_I^* = \frac{n[(x\theta_c+(1-x)\theta_d)][x\epsilon_c+(1-x)\epsilon_d)]}{2nx(x-1)+n+1}$

of permits that corresponds to the aggregate emissions target, such that $L = E_A^*$. However, under credit trading it is not directly clear how to reach $E^* = E_I^*$. We see from Table 1 that there are usually two levels of the weighted average of the emissions intensity of the clean and dirty good that yield the same E_I^*:

$$x^* = \frac{n\left(2E_I^* + \theta_c\epsilon_d + \theta_d\epsilon_c - 2\theta_d\epsilon_d\right) \pm \sqrt{na}}{2n\left(2E_I^* + (\theta_c - \theta_d)(\epsilon_d - \epsilon_c)\right)}, \tag{32}$$

where $a \equiv -4E_I^*\left(2E_I^* + (\theta_c - \theta_d)(\epsilon_d - \epsilon_c)\right) + 4E_I^* n\left(\theta_c\epsilon_c + \theta_d\epsilon_d - E_I^*\right) + n\left(\theta_c\epsilon_d - n\theta_d\epsilon_c\right)^2$. Using the unconstrained emissions $\bar{E}^*$ as shown by (13), this can be rewritten such that the relevant root becomes:[6]

$$x^* = \frac{1}{2} + \frac{(n+2)\left[n\left(\theta_c\epsilon_c - \theta_d\epsilon_d\right) + \sqrt{n^2\left(\theta_c\epsilon_d - \theta_d\epsilon_c\right)^2 - 4E_I^* n(n+2)(E_I^* - \bar{E}^*)}\right]}{2n\left(2(n+2)(E_I^* - \bar{E}^*) + n\left(\theta_c + \theta_d\right)\left(\epsilon_c + \epsilon_d\right)\right)}. \tag{33}$$

From Table 1 we know that x^* equals the long run equilibrium under credit trading in (32). In the Appendix we prove the following:

Proposition 1 *Under credit trading, if the clean sector has the highest cost margin on emissions ($\phi_c > \phi_d$), then the long run equilibrium proportion of firms in the clean sector, s_I^*, increases continuously from the unconstrained equilibrium $\bar{s}^*$ as the aggregate emission level E_I^* is reduced from the unconstrained level $\bar{E}^*$. If the dirty sector has the highest cost margin on emissions ($\phi_d > \phi_c$), then s_I^* jumps up initially as E_I^* is reduced from $\bar{E}^*$, after which it increases continuously.*

Figures 1 and 2 illustrate this proposition. In Figure 1, the clean sector has the highest cost margin on emissions ($\phi_c > \phi_d$), so that s_I^* increases continuously from its unconstrained

[6] See appendix for the identification of this root.

value of 0.317 as aggregate emissions are reduced from their unconstrained level of 8.07. In Figure 2, the dirty sector faces the highest cost margin on emissions ($\phi_d > \phi_c$), so that as soon as emissions are reduced from their unconstrained level of 3.97, s_I^* jumps up from 0.317 to 0.365. From there it increases continuously as aggregate emissions are reduced further.

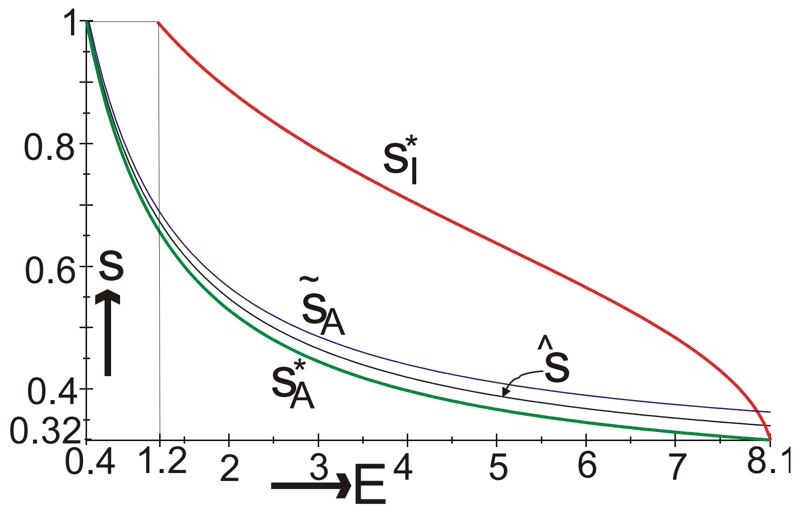

Figure 1: Long run equilibrium values when the clean good has the highest cost margin on emissions ($n = 20, \theta_c = 5, \theta_d = 10, \epsilon_c = \frac{1}{4}, \epsilon_d = \frac{3}{4}$)

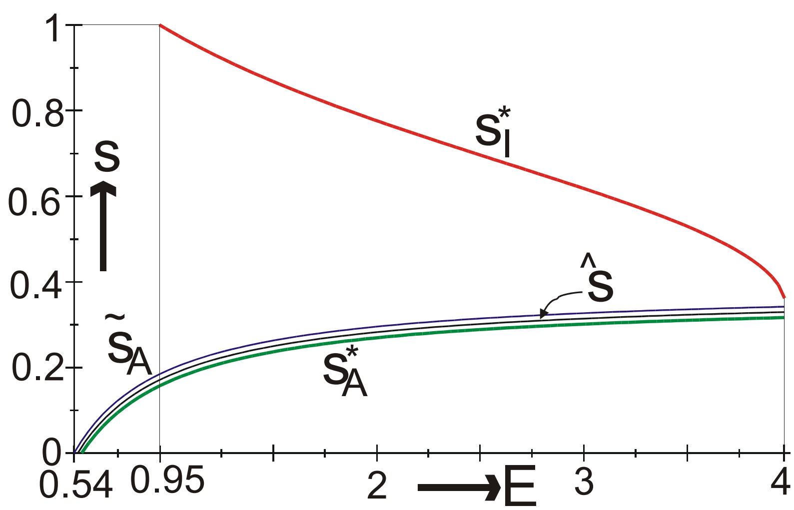

Figure 2: Long run equilibrium values when the dirty good has the highest cost margin on emissions ($n = 20, \theta_c = 5, \theta_d = 10, \epsilon_c = \frac{1}{5}, \epsilon_d = \frac{1}{3}$)

4.2 Environmental stringency and impact on the long run equilibrium

In this section we examine the effect of stricter environmental policy on the size of the clean sector at the long run equilibrium. Using the equilibrium given in Table 1, with permit trading we get:

$$\frac{\partial s_A^*}{\partial L} = \frac{(\phi_d - \phi_c)\epsilon_c\epsilon_d(2n\epsilon_c\epsilon_d + (n+1)(\epsilon_c - \epsilon_d)^2)}{n[(\phi_c - \phi_d)(\epsilon_d - \epsilon_c)\epsilon_c\epsilon_d + L(\epsilon_c + \epsilon_d)]^2}. \tag{34}$$

The sign, which depends on the first term in brackets in the numerator, is in line with our analysis in Section 3. When the clean (dirty) sector has the highest cost margin on emissions [i.e., $\phi_c > (<)\ \phi_d$] and permit trading is introduced in the unconstrained equilibrium, firms will start moving towards the clean (dirty) sector and there will ultimately be more (fewer) clean firms in the long run equilibrium the stricter is the cap on pollution.

Proposition 2 *With permit trading, if the clean sector has the highest cost margin on emissions ($\phi_c > \phi_d$), then the long run equilibrium proportion of firms in the clean sector, s_A^*, is increasing in the strictness of environmental policy (lower cap L) and above the unconstrained level $\bar{s}^*$. If the dirty sector has the highest cost margin on emissions ($\phi_d > \phi_c$), then s_A^* is decreasing in the strictness of environmental policy and even below $\bar{s}^*$.*

This proposition is also illustrated in Figures 1 and 2. In Figure 1, the clean good has the highest cost margin on emissions ($\phi_c > \phi_d$), so that s_A^* increases as aggregate emissions are reduced. In Figure 2, the dirty good has the highest cost margin on emissions ($\phi_d > \phi_c$), so that s_A^* decreases as aggregate emissions are reduced.

We now turn to a comparison of the long run equilibria.

Proposition 3 *Credit trading results in a strictly larger clean sector compared to permit trading for any binding cap on pollution. That is, $s_I^* > s_A^*$ for all E^* below the unconstrained emission level $\bar{E}^*$ given by (13).*

Proof. In Table 1, substituting $x = s_A^*$ into E_I^* and subtracting L yields:

$$E_I^*|_{x=s_A^*} - L = \frac{(\bar{E}^* - L)(n+2)}{L^2(n+2) + n(\theta_c\epsilon_d - \theta_d\epsilon_c)^2} > 0$$

Thus, issuing L permits under permit trading leads to s_A^*, and imposing this s_A^* as a standard under credit trading would lead to higher emissions than L. Since $dE_I^*/ds_I^* < 0$ from Proposition 1, reaching an emission level of L requires a stricter standard than s_A^*, i.e., $s_I^* > s_A^*$. ■

The intuition behind Proposition 3 is the following. Under the permit trading scheme each firm is endowed with a "commodity", i.e., the permit. For a given the distribution of firms in the clean and dirty sector (the state s), both clean and dirty firms can potentially sell permits depending on the profit opportunities. Firms utilize the permit as they produce output, which they then sell for a profit. The permit price is essentially the shadow value of profit for a given level of s. Put differently, producing a unit of output has an opportunity cost in terms of the lost permit revenue that could have been earned in the permit market. In contrast, under emissions trading based on intensity targets only clean firms can supply the "commodity", i.e., the credit. The credit can only be created by producing a unit of clean output. Therefore, under a credit trading scheme firms in the clean sector have a *negative* opportunity cost of production. Compared to permit trading a clean firm now has two market sources of revenue from producing a unit of output: the output market *and* the credit market. Thus, under permit trading clean firms *exercise* allowances (the permits) as they produce output whereas under credit trading they *create* allowances (the credits) as they produce output. This implies that credits are similar to providing clean firms with an implicit output subsidy equal to the credit revenue per unit of output (Dewees, 2001; Fischer, 2003), which provides an extra incentive to switch to become a clean firm in the long run. Under a permit scheme all emissions imply a permit cost whereas under credit trading only dirty-firm emissions implies a cost. Under a credit scheme clean firm emissions produce credit revenue.

5 Welfare

In this section we will determine the welfare optimum for a given level of emissions E in the long run equilibrium where firms' profit is equalized between the clean and dirty sector. We then compare the welfare optimum to the long run equilibrium under permit and credit trading, followed by a comparison of welfare under credit and permit trading.

Welfare consists of consumer surplus, net producer surplus and the value of permits, minus environmental damage. Since we are comparing permit and credit trading for a given equal level of emissions in the long run equilibrium, environmental damage is the same in what follows. This means we can abstract from including environmental damage explicitly, hence making the analysis more transparent. We define net producer surplus as the firm's profits after paying for the emission allowances. With permit trading this is the first term on the RHS of (21); with credit trading it simply equals the firm's profits π_{iI} in (25). The value of permits, $v\bar{e}_i$ in (21), is also a part of the firm's profits if they are grandfathered to firms. In case the permits would be auctioned, the value would accrue to the government. In graphical terms, welfare W consists of the area between the demand curves $\alpha_i - Q_i$ and the marginal cost curves c_i $(i = c, d)$, or formally:

$$\begin{aligned} W &= \theta_c Q_c + \theta_d Q_d - \frac{1}{2}(Q_c^2 + Q_d^2) \\ &= \theta_c n s q_c + \theta_d n(1-s) q_d - \frac{(nsq_c)^2 + (n(1-s)q_d)^2}{2}. \end{aligned} \tag{35}$$

We will now compare welfare in the long run equilibria under permits and credits under the restriction that total emissions do not exceed $E = E^*$ as given in (12). Substituting this expression into (35), we can express welfare as a function of s:

$$W = \frac{\theta_c s E}{s\epsilon_c + (1-s)\epsilon_d} + \frac{\theta_d (1-s) E}{s\epsilon_c + (1-s)\epsilon_d} - \frac{1}{2}\left[\left(\frac{sE}{s\epsilon_c + (1-s)\epsilon_d}\right)^2 + \left(\frac{(1-s)E}{s\epsilon_c + (1-s)\epsilon_d}\right)^2\right]. \tag{36}$$

Differentiating (36) with respect to s and solving yields the following welfare-maximizing size of the clean sector:

$$\hat{s} = \frac{E\epsilon_c + (\phi_c - \phi_d)\,\epsilon_c \epsilon_d^2}{E\,(\epsilon_c + \epsilon_d) + (\phi_c - \phi_d)\,(\epsilon_d - \epsilon_c)\,\epsilon_c \epsilon_d}. \tag{37}$$

Differentiating (37) with respect to E one obtains:

$$\frac{d\hat{s}}{dE} = \frac{(\phi_d - \phi_c)\left(\epsilon_c^2 + \epsilon_d^2\right)\epsilon_c \epsilon_d}{\left[E\,(\epsilon_c + \epsilon_d) + (\phi_c - \phi_d)\,(\epsilon_d - \epsilon_c)\,\epsilon_c \epsilon_d\right]^2}. \tag{38}$$

When emissions E decrease, the optimal size of the clean sector $\hat{s}$ increases (decreases) if the clean (dirty) good has the highest cost margin on emissions, i.e., $\phi_c > (<)\ \phi_d$. Intuitively, in the welfare maximum the welfare margin on emissions — i.e., the welfare increase from an increase in emissions — is the same in both sectors, implying $(p_c - c_c)/\varepsilon_c = (p_d - c_d)/\varepsilon_d$, or writing out, $\phi_c - \frac{sq}{\varepsilon_c} = \phi_d - \frac{(1-s)q}{\varepsilon_d} = \omega$. A decrease in overall emissions would prompt a decrease in output, q. Keeping the size of the clean sector s constant, this decrease in pollution would raise the welfare margin on emissions in the clean sector by $s/\varepsilon_c = (\phi_c - \omega)/q$ and in the dirty sector by $(1-s)/\varepsilon_d = (\phi_d - \omega)/q$. When $\phi_d > \phi_c$ the welfare margin would increase more in the dirty sector and would hence be higher in the dirty sector. To restore equality of welfare margins, firms would have to move from the clean to the dirty sector. Thus when $\phi_d > \phi_c$, the size of the clean sector decreases when aggregate emissions go down. Conversely, when $\phi_c > \phi_d$, the size of the clean sector increases when emissions decrease.

Comparing (38) with (34), we see that the welfare maximizing size of the clean sector $\hat{s}$ and the long run size of the clean sector under permit trading s_A^* move in the same direction as emissions E decrease. Comparing the optimal $\hat{s}$ in (37) with the equilibrium s_A^* under permits in Table 1, we obtain:

$$s_A^* - \hat{s} = -\frac{L(\epsilon_d - \epsilon_c)}{n\left[E\,(\epsilon_c + \epsilon_d) + (\phi_c - \phi_d)\,(\epsilon_d - \epsilon_c)\,\epsilon_c \epsilon_d\right]} < 0. \tag{39}$$

The term in square brackets on the RHS is clearly positive for $\phi_c > \phi_d$. For $\phi_d > \phi_c$, since the term is increasing in E, its lowest value is found for the minimum value of E, which is where $\hat{s} = 1$ in (37). Thus we find that for $\phi_d > \phi_c$ the term in square brackets on the RHS of (39) exceeds $(\phi_d - \phi_c)\left(\epsilon_c^2 + \epsilon_d^2\right)\epsilon_c > 0$.

We see that $s_A^* < \hat{s}$ for finite market size n; $s_A^* \to \hat{s}$ if $n \to \infty$, i.e., under perfect competition permit trading would implement the first-best outcome. Under imperfect competition production per firm is too low. By (12) this means that production is, on average, too dirty and the proportion of firms in the clean sector is too low. Figures 1 and 2 illustrate that while the optimal $\hat{s}$ moves in the same direction as s_A^* under permit trading, $\hat{s}$ always exceeds s_A^* for a given level of emissions. In sum:

Proposition 4 1. *When the clean (dirty) sector has the highest cost margin on emissions [i.e., $\phi_c > (<)\ \phi_d$], the long run welfare maximizing size of the clean sector, $\hat{s}$, increases (decreases) continuously as E^* is reduced from the long run unconstrained equilibrium emissions level $\bar{E}^*$.*

2. *While the long run equilibrium under permit trading s_A^* moves in the same direction as the welfare optimum $\hat{s}$ when E^* changes, $s_A^* < \hat{s}$ for any given level of E^*.*

Turning to the comparison with credit trading and the welfare-maximizing $\hat{s}$, let us start with the case where the clean good has the highest cost margin on emissions ($\phi_c > \phi_d$), which means that the long run equilibrium s_I^* as well as the welfare-maximizing $\hat{s}$ are decreasing in emissions E. Under credit trading the proportion of clean firms at the unconstrained emission level $\bar{E}^*$ is $s_I^*(\bar{E}^*) = s_A^*(\bar{E}^*) = \bar{s}^* < \hat{s}(\bar{E}^*)$ by (39). That is, for a very high level of emissions, close to $\bar{E}^*$, the clean sector is too small. As emissions decrease both s_I^* and $\hat{s}$ rise, but the former rises faster, so that $s_I^* = \hat{s}$ occurs at a unique value of emissions $E \in \left(0, \bar{E}^*\right)$. For lower values of emissions $s_I^* > \hat{s}$. This is illustrated in Figure 1, where $s_I^* < \hat{s}$ for E between 8.01 and 8.07 and $s_I^* > \hat{s}$ for all $E < 8.01$.

When the dirty sector has the highest cost margin on emissions ($\phi_d > \phi_c$), the welfare-maximizing value of $\hat{s}$ decreases from $\hat{s}(\bar{E}^*) > \bar{s}^*$ when emissions are reduced, but s_I^* first jumps up and then increases continuously when E is reduced. From (13), (33) and (37) we see that just below $\bar{E}^*$, s_I^* exceeds $\hat{s}$ if and only if:

$$2n\left(\theta_d\epsilon_c^2 - \theta_c\epsilon_d^2\right)(\epsilon_c + \epsilon_d) + n^2(\phi_d - \phi_c)\left(\epsilon_d^2 - \epsilon_c^2\right)\epsilon_c\epsilon_d > (n+1)(\theta_c + \theta_d)(\epsilon_d - \epsilon_c)^3$$

This condition is satisfied if and only if:

$$n > \hat{n} \equiv \frac{\sqrt{\left(\epsilon_c^2 + \epsilon_d^2\right)^2 Z^2 + 4\epsilon_c\epsilon_d(\phi_d - \phi_c)\left(\epsilon_d^2 - \epsilon_c^2\right)(\theta_c + \theta_d)(\epsilon_d - \epsilon_c)^3} - Z\left(\epsilon_c^2 + \epsilon_d^2\right)}{2\epsilon_c\epsilon_d(\phi_d - \phi_c)\left(\epsilon_d^2 - \epsilon_c^2\right)} \tag{40}$$

with $Z \equiv \theta_c\epsilon_c - 3\theta_c\epsilon_d + 3\theta_d\epsilon_c - \theta_d\epsilon_d$. Since s_I^* is decreasing and $\hat{s}$ is increasing in emissions E, $s_I^* > \hat{s}$ for all $E \leq \bar{E}^*$ if $n > \hat{n}$. This is the case in Figure 2, where $\hat{s} = 0.329$ at $E = \bar{E}^*$, but s_I^* jumps up to 0.365 when E is reduced from $\bar{E}^*$. If $n < \hat{n}$ then $s_I^* < \hat{s}$ for very high E (close to $\bar{E}^*$). With s_I^* decreasing and $\hat{s}$ increasing in E, $s_I^* = \hat{s}$ occurs at a unique value of $E \in \left(0, \bar{E}^*\right)$. For lower values of E, $s_I^* > \hat{s}$. Summarizing, we have:

Proposition 5

1. *When the clean sector has the highest cost margin on emissions ($\phi_c > \phi_d$), the long run equilibrium under credit trading s_I^* is below the optimal size of the clean sector $\hat{s}$ for very high E^* close to $\bar{E}^*$, but above optimal for all other E^*.*

2. *When the dirty sector has the highest cost margin on emissions ($\phi_d > \phi_c$), s_I^* exceeds $\hat{s}$ for all E^* if $n > \hat{n}$, with $\hat{n}$ defined by (40). If $n < \hat{n}$ then s_I^* is below $\hat{s}$ for very high E^* close to $\bar{E}^*$, but exceeds $\hat{s}$ for all other E^*.*

Let us now compare welfare with permits and credits at the long run equilibrium. We know that there are too few clean firms under permits and there are more clean firms under credits than permits. Thus, when there are too few clean firms under credits, welfare is higher under credits (because $s_A^* < s_I^* < \hat{s}$). However, when there are too many clean firms under credits, there may be so many that welfare is lower than under permits. To push the analysis a bit further it is useful to define $\tilde{s}_A > \hat{s}$ as the proportion of clean firms that yields the same welfare level as $s_A^* < \hat{s}$. Welfare under credits is higher (lower) than under permits if $s_I^* < (>)\ \tilde{s}_A$. From Table 1 and (36) we find:

$$\tilde{s}_A = \frac{E\left((1+n)\epsilon_c^3 + \epsilon_d^3 + (1+n)\epsilon_c\epsilon_d^2 - 3\epsilon_c^2\epsilon_d\right) + (\phi_c - \phi_d)\epsilon_d z}{E((2+n)\left(\epsilon_c^3 + \epsilon_d^3\right) + (n-2)\epsilon_c\epsilon_d(\epsilon_c + \epsilon_d)) + (\phi_c - \phi_d)(\epsilon_d - \epsilon_c) z}, \tag{41}$$

with $z \equiv \epsilon_c\epsilon_d[2(\epsilon_d - \epsilon_c)^2 + n(\epsilon_c^2 + \epsilon_d^2)]$. Following s_A^* and $\hat{s}$, $\tilde{s}_A$ is decreasing (increasing) in emissions for $\phi_c > (<)\ \phi_d$, as illustrated in Figures 1 and 2.

Let us start with the case where the clean good has the highest cost margin on emissions ($\phi_c > \phi_d$). With credit trading the equilibrium at the laissez-faire level $\bar{E}^*$ is $s_I^*(\bar{E}^*) = s_A^*(\bar{E}^*) = \bar{s}^* < \hat{s}(\bar{E}^*) < \tilde{s}_A(\bar{E}^*)$. Both s_I^* and $\tilde{s}_A$ rise as emissions go down, but the former rises faster so that $s_I^* = \tilde{s}_A$ occurs at a unique value of $E \in (0, \bar{E}^*)$. For lower values of E, $s_I^* > \tilde{s}_A$. In this case, credits lead to higher welfare than permits for very lenient environmental policy (E between 7.92 and 8.07 in Figure 1), but to lower welfare for stricter policy. When the dirty good has the highest cost margin on emissions ($\phi_d > \phi_c$), then from equations (13), (33) and (41), s_I^* just below $\bar{E}^*$ exceeds $\tilde{s}_A$ if and only if:

$$n^2(\phi_d - \phi_c)(\epsilon_c^2 + \epsilon_d^2)\epsilon_c\epsilon_d + 2n((\theta_c + \theta_d)d_1 + \theta_d d_2) > 2d_3(\theta_c + \theta_d),$$

with $d_1 \equiv \epsilon_c^3 + 2\epsilon_c^2\epsilon_d + \epsilon_c\epsilon_d^2 - 2\epsilon_d^3$, $d_2 \equiv \epsilon_c^3 + \epsilon_c^2\epsilon_d + \epsilon_c\epsilon_d^2 + \epsilon_d^3$ and $d_3 \equiv \epsilon_d^3 + \epsilon_d^2\epsilon_c - \epsilon_d\epsilon_c^2 - \epsilon_c^3$. This inequality holds if and only if:

$$n > \tilde{n} \equiv \frac{\sqrt{((\theta_c + \theta_d)d_1 + \theta_d d_2)^2 + 2(\phi_d - \phi_c)(\epsilon_c^2 + \epsilon_d^2)\epsilon_c\epsilon_d d_3(\theta_c + \theta_d)} - (\theta_c + \theta_d)d_1 - \theta_d d_2}{(\phi_d - \phi_c)(\epsilon_c^2 + \epsilon_d^2)\epsilon_c\epsilon_d} \tag{42}$$

Since s_I^* is decreasing and $\tilde{s}_A$ is increasing in E, $s_I^* > \tilde{s}_A$ for all $E \leq \bar{E}^*$ if $n > \tilde{n}$. In this case, permit trading leads to higher welfare than credit trading. This is the case in Figure 2, where $\tilde{s}_A = 0.342$ at $E = \bar{E}^*$, but s_I^* jumps up to 0.365 when E is reduced from $\bar{E}^*$. If $n < \tilde{n}$, $s_I^* < \tilde{s}_A$ for very high E. With s_I^* decreasing and $\hat{s}$ increasing in E, so that $s_I^* = \tilde{s}_A$ occurs at a unique value of $E \in (0, \bar{E}^*)$. For lower values of aggregate emissions $s_I^* > \tilde{s}_A$. In this case, credits lead to higher welfare than permits for very lenient environmental policy, but to lower welfare for stricter policy.

Proposition 6 *1. When the clean sector has the highest cost margin on emissions ($\phi_c > \phi_d$), long run welfare is higher under credit trading than under permit trading for very high E^* close to $\bar{E}^*$, but permit trading leads to higher welfare for all other E^*.*

2. When the dirty sector has the highest cost margin on emissions ($\phi_d > \phi_c$), long run welfare is higher with permit trading for all E^* if $n > \tilde{n}$, with $\tilde{n}$ given by (42). If $n < \tilde{n}$, long run welfare is higher with credit trading for very high E^* close to $\bar{E}^*$, but permit trading leads to higher welfare for all other E^*.

Finally, let us compare the different welfare components — consumer surplus, net producer surplus and the value of permits — for both emissions trading schemes. Obviously, the value of permits is only relevant for permit trading. Given linear demand with slope normalized to -1, consumer surplus for each type is $(Q_i)^2/2$ $(i = c, d)$, and aggregate consumer surplus is then $CS^* = (Q_c^*)^2/2 + (Q_d^*)^2/2$. Defining $\Delta CS = CS_I - CS_A$ as the consumer surplus advantage of the credit trading scheme, solving $\Delta CS = 0$ for x one obtains:

Proposition 7 *Credit trading results in strictly greater equilibrium consumer surplus compared to permit trading for any binding cap on pollution.*

Proof. Define $\Delta CS = CS_I - CS_A$ as the consumer surplus advantage of the credit trading scheme. Then, solving $\Delta CS = 0$ for x one obtains $\bar{x} = \frac{\theta_c(n+1)-\theta_d}{n(\theta_c+\theta_d)}$ and an irrelevant root $\breve{x} = \frac{\epsilon_d}{\epsilon_d-\epsilon_c}$, which is strictly greater than one for all $\epsilon_d > \epsilon_c > 0$. Note from Table 1 that the cap $L = 0$ implies this irrelevant root $s_A^* = \breve{x} = \frac{\epsilon_d}{\epsilon_d-\epsilon_c}$. If the cap is non-binding, the equilibrium is where $q_{c_A} = q_{d_A} \iff \frac{\theta_c}{sn+1} = \frac{\theta_d}{(1-s)n+1}$ and the unconstrained equilibrium is: $s_A^* = \bar{x} = \frac{\theta_c(n+1)-\theta_d}{n(\theta_c+\theta_d)}$. Direct evaluation for all values of $x > \bar{x}$ shows that $\Delta CS > 0$. ■

The reason why consumer surplus is unambiguously higher under credit trading at the long run equilibrium is the following. Producing output under a credit trading scheme creates a credit, which can be sold. This tends to increase clean output and consequently consumer surplus. With higher clean output, a greater supply of credits reduces the price, making dirty production less expensive than when the clean sector is relatively small, i.e., when there are only a few number of firms in the clean sector. The marginal cost of pollution is not fully included in the final output price because credits only impose a cost on those emissions that exceed the baseline activity level (e.g., Dewees, 2001). By contrast, with permits every unit of production and pollution implies a cost. Since the costs of pollution are lower under a credit scheme, output prices also tend to be lower under credits compared to permits, resulting in greater consumer surplus.

A similar line of argument can be followed to compare net producer surplus across both emissions trading schemes. Total net producer surplus is $PS^* = n(q_i)^2$ since clean and dirty firms have equal profit for a given regime in the long run equilibrium. The comparison reduces to comparing quantities [see (21) and (25)] which gives us:

Proposition 8 *Credit trading results in strictly greater equilibrium net producer surplus compared to permit trading for any binding cap on pollution.*

Proof. As before, define $\Delta PS = PS_I - PS_A$ as the net producer surplus advantage of the credit trading scheme. Solving $\Delta PS = 0$ for x yields exactly the same relevant root $\bar{x}$ as in (8).[7] Direct evaluation shows $\Delta PS > 0 \; \forall x > \bar{x}$. ■

Again, a tradable credit acts as an implicit subsidy to firms active in the clean sector. Since credits can only be created by producing clean output, this increases the number of firms in the clean sector. However, as the clean sector grows compared to the dirty sector, the relative profitability of firms in the dirty sector enhances due to less competitive pressure. For a given regime where profits are equalized, anything that increases clean profits will also increase dirty profits.

Comparing Propositions 7 and 8 to Proposition 6, we can conclude that while consumer surplus and net producer surplus are higher under credit trading, the value of permits under permit trading is so large that usually permits lead to higher overall welfare.

[7] The other root is the same one obtained earlier, i.e., $\breve{x} = \frac{\epsilon_d}{\epsilon_d-\epsilon_c}$. In addition, there are two imaginary roots that have real portions greater than one and are thus outside the relevant range.

6 Conclusions

This paper analyzes and compares the two main emissions trading design schemes — trading on the basis of an absolute cap and trading on the basis of pollution intensities — in a two-sector model with imperfect output competition. Firms choose output to maximize profit in the short run, given they are in the clean or the dirty sector. In the long run, firms switch sectors until profits are equalized. Given this framework, the analyses provides the following insights.

First, imposing environmental policy through emissions trading on the basis of an absolute cap (permit trading) does not automatically induce the clean sector to grow, as is often presumed. We find that a more stringent cap under permit trading induces a greater number of firms to switch to the clean sector only when the clean sector has a higher cost margin on emissions. In contrast, emissions trading on the basis of pollution intensities (credit trading) unambiguously results in a strictly greater number of clean firms in the long run. Via the use of emission standards, credit trading is effective in expanding the clean sector even when clean firms face a higher marginal cost relative to firms producing output in the dirty sector.

Second, while credit trading results in more clean firms than permit trading, it usually leads to too many clean firms. The size of the clean sector under credit trading is usually higher than the welfare-maximizing level. On the other hand, permit trading induces too few firms to switch to the clean sector in the long run. However, permit trading leads to higher long run welfare than credit trading, except when environmental policy is very lenient. Indeed, when the dirty sector has the higher cost margin on emissions, and permit trading leads to more dirty firms, it is welfare-maximizing to have more dirty firms.

While permit trading usually leads to higher overall welfare, consumers are better off under credit trading, because output is higher and prices are lower compared to permit trading. Producers, on the other hand, are better off under permit trading if there is complete grandfathering; if permits were auctioned, producers would prefer credit trading. Partial auctioning of permits and spending the revenue on compensating consumers might bring consumers around to permit trading while still retaining the producers' support. However, political haggling and lobbying over the share of permits to be auctioned and over spending the auction revenue may become very costly and distracting (e.g., MacKenzie and Ohndorf, 2011). Credit trading, where by default producers have the rights to emit (indeed, firms can create them), avoids this problem.

A Appendix

A.1 Derivation of first-order conditions (19) and (23)

Let us first concentrate on (19). Using (1) and rewriting as $q_i = e_i/\epsilon_i$, profit is written as a constrained optimization problem in firm-level emissions. For firm $f = 1, \ldots, n$ of type $i = c, d$, substituting (3) and (1) into the profit function (14) gives:

$$\max_{e_i} \pi_i^f = (\theta_i - q_i^f - \sum q_i^{-f})q_i^f + v(\bar{e}_i - e_i^f).$$

Eliminating quantity and writing this in terms of emissions we have:

$$\max_{e_i} \pi_i^f = \frac{e_i^f}{\epsilon_i}\left(\theta_i - \frac{e_i^f}{\epsilon_i} - \sum q_i^{-f}\right) + v(\bar{e}_i - e_i^f).$$

The first order condition is:

$$\frac{1}{\epsilon_i}\left(\theta_i - \frac{2e_i^f}{\epsilon_i} - \sum q_i^{-f}\right) - v = 0,$$

which will be the same for any firm of type i, hence symmetry and simplification results in (19). ■

Next, the first order condition for the credit trading scheme. Following the same procedure, substitution of (3) and (1) into the profit function (17) gives:

$$\max_{e_i} \pi_i^f = (\theta_i - q_i^f - \sum q_i^{-f})q_i^f + w\left(\delta_i q_i - e_i\right).$$

Again, eliminating quantity and writing this in terms of emissions we have:

$$\max_{e_i} \pi_i^f = \frac{e_i^f}{\epsilon_i}\left(\theta_i - \frac{e_i^f}{\epsilon_i} - \sum q_i^{-f}\right) + w\left(\frac{\delta_i e_i}{\epsilon_i} - e_i\right).$$

The first order condition is:

$$\frac{1}{\epsilon_i}\left(\theta_i - \frac{2e_i^f}{\epsilon_i} - \sum q_i^{-f}\right) + w\left(\frac{\delta_i - \epsilon_i}{\epsilon_i}\right) = 0,$$

which will be the same for any firm of type i, hence symmetry and simplification results in (23). ■

A.2 Derivation of profit functions (21) and (25)

Under permit trading profit is represented by (14). Using the demand function (3) and emissions function (1), the profit function (14) becomes:

$$\begin{aligned}
\pi_i &= (\alpha_i - Q_i - c_i)q_i + v\left(\bar{e}_i - e_i\right) \\
&= (\theta_i - Q_i)q_i + v\left(\bar{e}_i - \epsilon_i q_i\right) \\
&= [\theta_i - v\epsilon_i - n_i(s)q_i]q_i + v\bar{e}_i.
\end{aligned}$$

Substituting the Cournot-Nash quantity (20) into the above expression gives (21):

$$\begin{aligned}
\pi_i &= \frac{\theta_i - \epsilon_i v(s,L)}{n_i(s)+1}\left(\theta_i - v\epsilon_i - n_i(s)\frac{\theta_i - \epsilon_i v(s,L)}{n_i(s)+1}\right) + v\bar{e}_i \\
&= (q_i(s,L))^2 + v\bar{e}_i.
\end{aligned}$$

■

Applying the same routine for the credit scheme, again using (3) and (1), the profit function (17) becomes:

$$\begin{aligned}\pi_i &= (\alpha_i - Q_i - c_i)q_i + w\,(\delta q_i - e_i) \\ &= (\theta_i - Q_i)q_i + w\,(\delta q_i - \epsilon_i q_i) \\ &= (\theta_i + w\,(\delta - \epsilon_i) - n_i(s)q_i)\,q_i^I.\end{aligned}$$

Substituting the Cournot-Nash quantity (24) into the above expression gives (25):

$$\begin{aligned}\pi_i &= \frac{\theta_i + w(\delta - \epsilon_i)}{n_i + 1}\left(\theta_i + w\,(\delta - \epsilon_i) - n_i(s)\frac{\theta_i + w(\delta - \epsilon_i)}{n_i + 1}\right), \\ &= (q_i(s,\delta))^2.\end{aligned}$$

■

A.3 Identification of the long run equilibrium (33)

Denote the two solutions for x^* in (32) by x_0^* and x_1^*, with $x_0^* \leq x_1^*$. We see that for $E_I^* = \bar{E}^*$:

$$\begin{aligned}x_0^* &= \frac{(1+n)\epsilon_c - \epsilon_d}{n\,(\epsilon_c + \epsilon_d)}, \qquad x_1^* = \bar{s}^* \qquad\qquad \text{for } \phi_c > \phi_d \\ x_0^* &= \bar{s}^*, \qquad x_1^* = \frac{(1+n)\epsilon_c - \epsilon_d}{n\,(\epsilon_c + \epsilon_d)} \qquad\qquad \text{for } \phi_c < \phi_d\end{aligned} \tag{43}$$

with $\bar{s}^*$ given by (8). It is clear from (33) that x_1^* is decreasing in E_I^*, because the numerator of the fraction on the RHS is decreasing in E_I^* and the denominator is increasing in E_I^*. It can also be shown that x_0^* is increasing in E_I^*. It follows from this and (43) that $x_0^* < \bar{s}^*$ and $x_1^* > \bar{s}^*$ for all $E_I^* < \bar{E}^*$. This means that x_0^* cannot be implemented, because x_0^* requires a more lenient standard than the unconstrained outcome and therefore not binding. However, x_1^* can be implemented, because it requires a stricter standard than the unconstrained outcome. Thus $s_I^* = x_1^*$ and equal to (33). ■

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