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Market Structure and Technology Diffusion Incentives under Alternative Environmental Policy Schemes

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Abstract

This paper compares emission taxes, subsidies, permits and credits with respect to the incentives they create to enhance technology diffusion under imperfect competition. Firms can adopt a "dirty" technology or a "clean" abatement technology. When the clean and dirty products are perfect substitutes, and clean firms face a net absolute advantage over dirty firms, permits and taxes provide the strongest incentive, followed by credits and subsidies respectively. This ranking order is reversed if there is a distortion on output. Subsidies can neutralize this distortion; subsidies stimulate output supply, which would normally be lower than optimal under perfect competition.

Keywords: market structure, environmental policy, technology diffusion, product differentiation, pollution control

JEL classification: L130; Q28; O300

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1 Introduction

A focal point in the development towards a more sustainable environment concerns the choice and impact of regulatory instruments on technological change. For instance, it can be expected that the implementation of those environmental policy instruments that induce a higher and faster degree of market penetration of environmentally benign technologies, will affect a reduction in the long run level of pollution positively (Kneese and Schultze [1975], Orr [1976]). The significance of short run policy decisions in relation to long run technological outcomes has also more recently been addressed in an extensive survey by Jaffe, Newell and Stavins [2000, p. 66] as they stress that "potential long run consequences of today's policy choices create a high priority for broadening and deepening our understanding of the effects of environmental policy on innovation and diffusion of new technology. (...) For both benefit-cost and cost-effectiveness analysis we need to know the magnitudes of these effects, and these magnitudes are likely to differ across markets, technologies and institutional settings."

This paper contributes to this area by gauging the long run technology diffusion incentives as created by different environmental policy instruments. Explicit attention will be paid to imperfectly competitive markets, since it is less unequivocal to what extent different environmental policy instruments stimulate the diffusion of pollution control technology within such market settings (Jaffe, Newell and Stavins [2000]). Moreover, taking a view encompassing imperfect rather than perfect competition seems also empirically justified, because most of the pollution intensive industries are concentrated (e.g., World Bank [1992], Fung and Maechler [2000]).

A number of papers have appeared that aim at establishing a ranking order between various environmental policy instruments regarding the extent by which they enhance the adoption and diffusion incentives of pollution control technology (Downing and White [1986], Milliman and Prince [1989], Jung, Krutilla and Boyd [1996], Requate and Unold [2003]). The central criterion in evaluating the different instruments is to compare the costs before and after adoption of the abatement technology, where the latter differs from a conventional "dirty" technology in terms of lower marginal abatement costs. The larger the savings in total cost due to adoption of the abatement technology, the stronger the adoption incentive is supposed to be.

Downing and White [1986], Milliman and Prince [1989] and Jung, Krutilla and Boyd [1996] assume that *all* firms adopt the abatement technology, i.e., technology diffusion is complete. Given this assumption, Downing and White [1986] conclude that effluent fees are superior to direct regulation in terms of adoption incentive. Moreover, they find that effluent fees and tradable permits basically provide equal adoption incentives. By ordering the firm-level adoption incentives from high to low, Milliman and Prince [1989] obtain a relative ranking order of (1) auctioned permits, (2) emission taxes and subsidies, (3) grandfathered permits and (4) direct controls. On an industry-wide level, Jung, Krutilla and Boyd [1996] find the same ranking as Milliman and Prince [1989].

Requate and Unold [2003] relax the assumption of a complete industry-wide adoption of abatement technology. They argue that in such a case the industry-wide cost savings do not reflect the adoption incentive of a single firm *in equilibrium*, thereby stressing the importance of equilibrium conditions. For example, in case of a tradable permit policy, the permit price falls when more firms adopt the abatement technology. This lower permit price is not only advantageous to the adopters of the new abatement technology but also to the non-adopting firms. In addition, REQUATE AND UNOLD [2003] show that grandfathered and auctioned permits provide equal adoption incentives.

In this paper too we will follow an "equilibrium approach". This implies that diffusion of abatement technology is endogenous and that only a fraction of all firms in the industry may adopt it, i.e., the industry can be heterogeneous. However, in contrast to the above mentioned studies on instrument ranking, we also address the output market and product differentiation.

There is a branch of literature that covers the output market effects in relation to the ranking of environmental policy instruments; however, at the same time may also synthesize with efficiency analyses. Seminal in this line of research is SPULBER [1985], who compared a system of auctioned permits with emission taxes. His analysis revealed that these instruments are both efficient in the long run in terms of entry. Provided that the emission tax and permit price are equal to marginal social damage, the optimal number of firms enter the market under free entry.

REQUATE [1995] asks whether Spulber's result also holds if the set of available technologies not just contains a single existing technology, but that firms can choose among different ones. He distinguishes two types of technology: one with low and one with high marginal abatement costs. The latter technology also incurs higher fixed costs. REQUATE [1995] models a perfectly competitive industry where the industry size is endogenous thus allowing free entry. He particularly examines whether emission taxes and auctioned permits yield a degree of adoption that is socially optimal and concludes that an emission tax basically always generates an incentive for complete adoption or no adoption at all, i.e., emission taxes may yield complete specialization in one of the two technologies. Furthermore, under a permit regime he finds the existence of a unique competitive equilibrium in which both types of technologies coexist for various permit allocation policies.

This result is also found by Requate [1998], again by taking the output market into account. The main difference with Requate [1995] is that the ranking between an effluent tax and auctioned permits is examined for a wide range of damage parameters. It is shown that the associated incentive depends highly on the social damage function and so there is no unique ranking order. For both sufficiently low and high damage parameters, taxes generate a higher incentive relative to auctioned permits, whereas permits perform better for an intermediate range of parameters. With respect to welfare, Requate [1998] finds that permits are always welfare increasing since they yield an efficient allocation of emissions after the introduction of a new technology.[1] On the other hand, an emission tax may generate a welfare reduction.

The output market is also modelled explicitly in the literature that examines the interrelationship between environmental policy and the internalization of social damages as a consequence of pollution. This literature differs in two ways from the previous mentioned work. First, the market for outputs features imperfect competition. Second, it does not so much address the issue of technology diffusion, but rather focuses on whether the implementation of environmental policy within such output markets may

[1] Under the assumption of a perfectly competitive permit market.

internalize pollution damages *optimally* (e.g., Buchanan [1969], Barnett [1980], Levin [1985], Ebert [1992], Requate [1993a], [1993b]). The general conclusion of these studies is that the optimal emission fee falls short of marginal social damage, which is due to the inflicted distortion on output in case of imperfect competition relative to the perfect competitive situation.

In this paper we explicitly abstract from efficiency arguments in the analysis because of the lack of adequate marginal damages from pollution data; we do, however, address efficiency implicitly.[2] The analysis in this paper is concerned with the diffusion incentives from the implementation of tradable permits, emission taxes, emission reduction subsidies and tradable credits. The latter is a combination of emission standards with credit trade, thus providing a market flavor to conventional measures of direct regulation by means of standards. Although an efficiency analysis is not explicitly accounted for in this paper, comparing environmental policy instruments on the basis of diffusion incentives remains an important issue for policy makers, since they still have to choose a policy instrument given the lack of good information on marginal damages from pollution (Keohane [1999]).

The aim of this paper is to compare the aforementioned instruments on the basis of diffusion incentives they provide within an imperfectly competitive market setting. In order to avoid an arbitrary comparison, we determine the diffusion equilibria such that all four policy measures generate equal aggregate emissions in equilibrium. We call these equilibria the "constrained equilibria" (CE). When determining the CE, we do not

[2] Relevant normative oriented contributions (without output market effects) are Fischer, Parry and Pizer [2003], Parry [1998], Biglaiser and Horowitz [1995] and Biglaiser, Horowitz and Quiggin [1995].

have to worry about adjusting for emissions afterwards and can directly compare the instruments on their diffusion incentive effects given total emissions are equal among the instruments in the corresponding equilibrium.

The structure of the paper is as follows. Section 2 presents the modeling framework. In Section 3, the four pollution control policies are introduced and the corresponding optimal output levels are derived. Section 4 is devoted to the process of technology diffusion and the associated diffusion equilibria. In Section 5, we compare and evaluate the diffusion equilibria of the four policy regimes. Conclusions are given in Section 6.

2 The model

This section presents a model which serves as the central device for analyzing the strategic behavior of technology adoption − and subsequently diffusion − and product differentiation. A first duopoly version of the model was introduced by Dixit [1979]. Friedman and Fung [1996] extended it to a N-size (two-country) oligopolistic market and transformed it into an evolutionary game model in order to analyze the effects of trade on firms' internal organizational structure. This version is also adopted here; however, instead of analyzing a two country setup, we focus on technology diffusion within a single polluting industry. For that purpose, we implement some changes in the cost structure and incorporate a pollution and environmental policy dimension, which is absent in the above studies.

2.1 The industry and product differentiation

Consider an oligopolistic industry comprising the set of firms $\Omega = \{1, 2, \ldots, N\}$, where the industry size N is assumed to be fixed.[3] A firm produces output with technology $j = \{d, c\}$: a conventional "dirty" technology ($j = d$) or a new "clean" abatement technology ($j = c$). Firms who employ the same technology are identical with respect to their demand and cost conditions and generate, therefore, identical output levels. Call q_d the output of a dirty technology firm and q_c the output of a clean technology firm.

Product differentiation comes from the distinction between the two types of goods due to the difference in the two technological features. What counts is that consumers perceive the two products as being different because of the associated different environmental characteristics. Because products are differentiated, two submarkets can be distinguished, i.e., the inverse demand functions read as:

$$p_d(Q_d, Q_c) = \alpha_d - \beta Q_d - \gamma Q_c, \tag{1}$$

$$p_c(Q_d, Q_c) = \alpha_c - \beta Q_c - \gamma Q_d.$$

Product differentiation is reflected by two parameters: γ and α_j. Parameter γ (relative to β) determines the degree of substitutability between the clean and dirty good, i.e., the degree of product heterogeneity. The goods are called independent when $\gamma = 0$. In case $\beta > \gamma > 0$, the goods are imperfect substitutes. The second aspect of product differentiation is measured by the intercepts α_d and α_c in equation (1). A higher α_j

[3] Although the inclusion of an entry/exit mechanism may yield efficient policy outcomes, we abstract from such a mechanism here. The reason is twofold. First, efficiency is not our focal point as explained in the introductory section. Second, Bresnahan and Reiss [1991] show that entry does not have a significant impact on the effects of competition in concentrated markets.

implies an absolute advantage (at equal quantities) in demand enjoyed by the firm that employs technology j (cf., Dixit [1979]). That is, there is a price premium on the clean (dirty) good if $\alpha_c > (<)\ \alpha_d$.

Equation (1) shows that prices are a function of aggregate output Q_j $(j = d, c)$. Now, define $s \in [0, 1]$ as the fraction of firms in the industry that currently employ the clean technology, i.e., s reflects the degree of diffusion of clean technology. Then, aggregate output Q_j can be written as:

$$\begin{aligned} Q_d(s) &= (1-s)Nq_d, \\ Q_c(s) &= sNq_c. \end{aligned} \tag{2}$$

Note that firm-level outputs q_j $(j = d, c)$ also depend on the state of diffusion s. However, for the sake of transparency, the explicit forms of these supply levels will be derived in subsection 3.2.

2.2 Costs and net absolute advantage

It is assumed that production costs of a firm with technology $j = d, c$ are proportional to output q_j:

$$c_j(q_j) = \vartheta_j q_j, \tag{3}$$

where $\vartheta_j > 0$ denotes the variable (and marginal) production costs. Due to reasons of energy-efficiency, the clean technology could face lower constant average variable costs relative to the dirty technology.

Recall that differences in the intercepts α_j of the price functions (1) reflect an absolute advantage in demand in producing either the clean or dirty good. Since α_j is not adjusted for variable costs, this is, however, a *gross* measure. Therefore, the *net* absolute advantage can be derived by relating α_j to the cost function (3). Following Dixit [1979], define

$$\theta_j = \alpha_j - \vartheta_j > 0, \tag{4}$$

reflecting the net absolute advantage of a technology j-mode firm. Whether the clean or dirty firm faces a net absolute advantage over the other depends on the price premium α_j and marginal cost ϑ_j.

2.3 Pollution

A firm adopting technology $j = d, c$ generates a negative externality in terms of emissions e_j. Like with costs, we assume a linear relationship between emissions and production. The emission function of a j-mode firm under policy regime k then equals:

$$e_j(q_j) = \zeta_j q_j, \tag{5}$$

where ζ_j is the emission/output ratio of technology j. By definition, the clean technology generates lower emissions per unit of production than the dirty technology, i.e., $\zeta_c < \zeta_d$.

3 Environmental policy and a firm's optimal output decision

3.1 The environmental policy regimes

Let k be the policy regime under consideration. We distinguish four pollution control policies: emission taxes ($k = tax$), emission reduction subsidies ($k = sub$), tradable emission permits ($k = per$) and tradable emission credits ($k = cre$). Under each regime there are two distinct decisions a firm has to make, which are of a short run and long run nature. The long run decision implies the technology choice. Given this choice of production mode, the short run decision implies how much to supply on the (sub)market in which the firm is engaged in order to maximize short run profits.

When outlining the different policies, it may be good to project them onto a no-regulation or "laissez faire" case ($k = lf$). Table 1 contains the profit functions π_j^k to be maximized for each policy regime k given technology adoption $j = d, c$. Each of the policies will be discussed systematically below.

Table 1: Profit functions under the different policy regimes

Policy	Profits π_j	Constraint
Laissez faire	$p_j(Q_d, Q_c)q_j - c_j(q_j)$	
Taxation	$p_j(Q_d, Q_c)q_j - c_j(q_j) - \tau e_j(q_j)$	
Subsidies	$p_d(Q_d, Q_c)q_d - c_d(q_d)$ $p_c(Q_d, Q_c)q_c - c_c(q_c) + \omega r(q_c)$	
Permits	$p_j(Q_d, Q_c)q_j - c_j(q_j) - \sigma e_j(q_j)$	$\sum_j \zeta_j Q_j = g$
Credits	$p_j(Q_d, Q_c)q_j - c_j(q_j) - \phi(e_j(q_j) - \delta q_j)$	$\sum_j \zeta_j Q_j = \delta \sum_j Q_j$

In case of laissez faire, profit maximization implies maximizing revenue over total costs. Total costs under this policy regime reflect only costs involved with production. Under a taxation regime every firm $i = 1, 2, \ldots, N$ has to pay a tax τ for each unit of emission generated through production. The tax rate is given for the firm and does not depend on diffusion s. Compared to laissez faire, the profit maximizing firm that adopts technology j now also has to consider the emission tax τ.

Whereas an emission tax affects firm-level profits adversely, the government can also influence profits in a positive way by subsidizing the amount of emission reduction that a firm accomplishes. A lump-sum subsidy can be interpreted as a policy directed towards the technology itself. Since we know that this is not always a credible instrument for affecting the environmental quality positively (e.g., Baumol and Oates [1988]), we introduce a form of subsidy that is more directed towards the potential level of emissions. Assume that the government wants to do so by introducing a subsidy ω per unit of emission reduction r. When a dirty firm wants to switch to an environmentally benign production process by adopting the clean technology, it reduces the amount of emissions caused by production. In turn, the level of emission reduction can be written as:

$$r(q_c) = (\zeta_d - \zeta_c) q_c. \tag{6}$$

Multiplying (6) with ω yields the total subsidy a firm receives when it adopts the clean technology. In case a firm sticks to the dirty technology, the profits to be maximized coincide with the profits under laissez faire.

Under permits, the control authority sets an industry-wide emission ceiling g. By following a grandfathering approach and given the number of N competitors, each single firm is initially endowed with a number of $m = g/N$ permits. Each permit allows a firm to emit one unit of the pollutant and the permits may be traded among firms. As we see in Table 1, profits equal revenues minus costs and the amount of permits the firm holds to cover emissions at price σ. It is assumed that firms are price takers on the tradable permit market.[4] The conditions for profit maximization include the demand and cost functions and assume that demand for outputs equals output supply. The market clearing condition for the permit market is $\sum_j \zeta_j Q_j = g$. The left-hand-side represents the market demand for permits, which is determined by the level and composition of output. The right-hand-side is the (fixed) supply of permits that has been made available by the government. In short, the constraint states the condition for equilibrium on the permit market: demand for permits equals permit supply.

Whereas under a permit system the control authority sets a limit on the total supply of emissions, in case of tradable emission credits the authority imposes an emission standard δ (see e.g., TIETENBERG [1999]). Emission standards with credit trade means that when a firm wants to emit more than the standard (multiplied with output) allows to, it can buy credits from firms that are capable to emit less than the emission standard and output would allow. The result is that, on average, the industry as a whole complies with the emission standard, but the individual firm has the flexibility to deviate from it. Under a combination of emission standards with credit trade, total emissions are not bound by an overall ceiling. If both total output of clean and dirty goods increases by, let's say 10 percent, total allowed emissions also increase by 10 percent. A firm's emission space is simply its production volume multiplied by the standard. A firm that emits less than its emission space allows to can sell its redundant amount of credits. So the essential difference with permit trade

[4] This assumption is credible since a government often imposes a permit policy on a whole set of different industries. The permit market can thus be perfectly competitive while at the same time the core business of the individual subindustries takes place in concentrated market settings.

is that the emission space under credits grows with the associated production growth, while the emission space is independent on changes in future changes of the individual firm's output volume.

To be feasible, the emission standard $\delta \in (\zeta_c, \zeta_d)$. Comparing profits under credits with permits shows that the difference is the emission standard δ only. However, the emission constraint under credits $\sum_j \zeta_j Q_j = \delta \sum_j Q_j$, which ensures equilibrium on the credit market, is now also subject to variability. That is, credit supply (the right-hand-side) now also depends on the level and composition of aggregate output Q_j instead of being fixed as under permits.

3.2 The output decision and derivation of the permit and credit price

Since firms are assumed to be profit maximizers, they choose optimal output levels given their technology choice and given the current distribution of clean and dirty technology in the industry, i.e., diffusion state $s \in [0, 1]$. Given a firm has adopted technology j, it chooses a non-negative output level q_j^k which maximizes profits π_j^k, considering the other firms' output decision as given, i.e., to maximize π_j^k as given in Table 1. The first-order conditions for profit maximization under the control policies $k = lf, tax, sub, per, cre$ are $d\pi_j^k / dq_j^k = 0$ $(j = d, c)$.[5] Substituting (2) into the first-order conditions and taking into account that the state of diffusion s is given when firms determine their output decision, the simultaneous solution to the first-order conditions yields the optimal Cournot-Nash firm-level quantities. Table 2 provides an overview of these optimal supply levels.

[5] The first-order conditions are given in the appendix.

Table 2: Firm-level Cournot-Nash quantites under the different policy regimes

Policy	$q_d^k(s)$	$q_c^k(s)$
Laissez faire	$\frac{\beta(sN+1)\theta_d-\gamma sN\theta_c}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$	$\frac{\gamma(1-s)N\theta_d-\beta((1-s)N+1)\theta_c}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$
Taxation	$\frac{\beta(sN+1)(\theta_d-\tau\zeta_d)-\gamma sN(\theta_c-\tau\zeta_c)}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$	$\frac{\gamma(s-1)N(\theta_d-\tau\zeta_d)-\beta((s-1)N-1)(\theta_c-\tau\zeta_c)}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$
Subsidies	$\frac{\beta(sN+1)\theta_d+\gamma sN(\omega(\zeta_c-\zeta_d)-\theta_c)}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$	$\frac{\gamma(s-1)N\theta_d-\beta((s-1)N-1)(\omega(\zeta_d-\zeta_c)+\theta_c)}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$
Permits	$\frac{\beta(sN+1)(\theta_d-\sigma\zeta_d)-\gamma sN(\theta_c-\sigma\zeta_c)}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$	$\frac{\gamma(s-1)N(\theta_d-\sigma\zeta_d)-\beta((s-1)N-1)(\theta_c-\sigma\zeta_c)}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$
Credits	$\frac{\beta(sN+1)(\theta_d-\phi(\zeta_d-\delta))-\gamma sN(\theta_c-\phi(\zeta_c-\delta))}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$	$\frac{\gamma(s-1)N(\theta_d-\phi(\zeta_d-\delta))-\beta((s-1)N-1)(\theta_c-\phi(\zeta_c-\delta))}{\beta^2(N+1)-(s-1)sN^2(\beta^2-\gamma^2)}$

The Cournot-Nash quantities are the market clearing conditions for the oligopolistic output market. However, we also need the market clearing conditions of the permit and credit market, which are reflected by the constraints $\sum_j \zeta_j Q_j = g$ and $\sum_j \zeta_j Q_j = \delta \sum_j Q_j$ respectively. As explained above, these constraints express the condition for equilibrium on the permit and credit market. Since it was assumed that firms are price takers on the permit and credit market, the permit price and credit price is given when a firm decides how much to produce to maximize profits. However, the emission prices do depend on the state of diffusion s. As a next step, let us derive the permit and credit price formally.

Under the permit regime, the condition $\sum_j \zeta_j Q_j = g$ requires that demand for permits equals the given permit supply. From the modelling structure it is clear that the permit price is not determined separately on the permit market, but by the simultaneous equilibrium on the permit and output market. If emissions tend to exceed the available quantity of permits, excess demand for permits is prevented by an increase in the permit price σ, which basically has the same effect on production as a higher emission tax. The marginal cost of clean and dirty output will rise, but more for the dirty product variant than the clean one, hence inducing profit maximizing oligopolistic firms to produce less and charge higher prices. Both the supply of clean and dirty firm-level output decrease, i.e., $\partial q_j^{per}/\partial\sigma < 0$ $(j = d, c)$. Lower output brings down emissions, thus restoring equilibrium between permit demand and permit supply. So the permit price has no direct effect on emissions, but influences them through its effect on the output market. When the permit price σ increases, both the price of the dirty and clean good increase, hence discouraging overall demand. An rising permit price implies that the price of the dirty good becomes relatively more expensive compared to the clean good, i.e., p_c^{per} decreases relative to p_d^{per}. Production of the dirty good will decrease relative to the output level of the clean firm. The substitution of clean for dirty output tends to decrease emissions. More precisely, in case the increase of total output threatens to push emissions upwards $-$ and above the cap g $-$ the rise in σ and the change in composition of output involves that total emissions stay below the emission ceiling g.

The permit price σ can be found by substituting the corresponding Cournot-Nash quantities $q_d^{per}(s)$ and $q_c^{per}(s)$ (as given in Table 2) into the constraint $\sum_j \zeta_j Q_j = g$. Then solving for σ yields the permit price as a function of diffusion s. After some rearranging the permit price can be written as:

$$\sigma(s) = \frac{a_0 + a_1 s + a_2 s^2}{a_3 + a_4 s + a_5 s^2}, \tag{7}$$

where the constants read:

$$
\begin{aligned}
a_0 &= \beta\left[g(N+1)\beta - \zeta_d N\theta_d\right], \\
a_1 &= N[g(\beta^2-\gamma^2)N + (\gamma N\theta_c - \beta(N-1)\theta_d)\zeta_d - (\beta(N+1)\theta_c - \gamma N\theta_d)\zeta_c], \\
a_2 &= N^2[g(\gamma^2-\beta^2) - (\gamma\theta_c - \beta\theta_d)\zeta_d + (\beta\theta_c - \gamma\theta_d)\zeta_c], \\
a_3 &= -\beta N\zeta_d^2, \\
a_4 &= -N[\beta((N-1)\zeta_d^2 + (N+1)\zeta_c^2) - 2\gamma N\zeta_d\zeta_c], \\
a_5 &= N^2[\beta(\zeta_d^2+\zeta_c^2) - 2\gamma\zeta_d\zeta_c].
\end{aligned}
$$

The credit price ϕ can be derived in the same way as the permit price. By substituting q_d^{cre} and q_c^{cre} (see Table 2) into the constraint $\sum_j \zeta_j Q_j = \delta \sum_j Q_j$ and solving for ϕ yields

$$
\phi(s) = \frac{b_0 + b_1 s + b_2 s^2}{b_3 + b_4 s + b_5 s^2}, \tag{8}
$$

where:

$$
\begin{aligned}
b_0 &= \beta(\delta-\zeta_d)\theta_d, \\
b_1 &= \left[\beta(N+1)(\delta-\zeta_c) - \gamma N(\delta-\zeta_d)\right]\theta_c + \left[\beta(N-1)(\delta-\zeta_d) - \gamma N(\delta-\zeta_c)\right]\theta_d, \\
b_2 &= N[((\gamma-\beta)\delta + \beta\zeta_c - \gamma\zeta_d)\theta_c + ((\gamma-\beta)\delta + \gamma\zeta_c - \beta\zeta_d)\theta_c], \\
b_3 &= -\beta(\delta-\zeta_d)^2, \\
b_4 &= 2\delta^2 N(\gamma-\beta) - \beta\zeta_c^2(N+1) + 2\delta\zeta_d(\beta(N-1)-\gamma N) + \beta\zeta_d^2(1-N) + \\
&\qquad 2\delta\zeta_c(\beta(N+1)-\gamma N) + \gamma\zeta_d\zeta_c, \\
b_5 &= 2\delta(\beta-\gamma)(\delta-\zeta_c) + \zeta_c(\beta\zeta_c - 2\gamma\zeta_d) + \zeta_d(2\delta(\gamma-\beta) + \beta\zeta_d).
\end{aligned}
$$

So far, we have outlined the industry structure and the different policy schemes. We will now focus on the diffusion process as based on the economic model outlined above and shall derive the diffusion equilibria under the various policy regimes.

4 Diffusion equilibria

Recall that we introduced the state variable s to represent the fraction of clean firms in the industry. It is interpreted as the degree of clean technology diffusion. We are particularly interested in the long run outcome of the diffusion process. The main question to be addressed here is: How far will the penetration of the clean technology go, i.e., what is the equilibrium level of diffusion?

For each diffusion state s, the corresponding Cournot equilibrium can be determined; that is, outputs, prices and profits in both the clean and dirty submarket. Subsequently, for each policy regimes k the profit differential Δ^k is defined as:

$$\Delta^k = \pi_c^k - \pi_d^k. \tag{9}$$

From (9) it is easy to see that employing the clean technology yields higher (lower) profits than the dirty technology if $\Delta^k > (<)\ 0$. Moreover, from (9) it directly follows that there is no incentive to switch technologies in case $\Delta^k = 0$. In the diffusion states at which this holds firms are indifferent between the two technologies, hence making this state a Nash equilibrium; it is the long run equilibrium degree of diffusion $\tilde{s}^k$, which is truncated below at 0 and above at 1. The interior solutions $\tilde{s}^k$ are dynamically stable (unstable) if $d\Delta^k/d\tilde{s}^k < (>)\ 0$ (cf., Friedman and Fung [1996]). To make a comparison between the different policy instruments more transparent, we assume that there is a unique interior diffusion equilibrium under all policy regimes, i.e., we assume that the profit differential Δ^k is strictly decreasing in s^k.[6]

[6] McGinty [2001] provides explicit parameter restrictions for the model discussed in Section 2 and

Given diffusion equilibrium uniqueness, an attempt can be made to rank the four policy instruments to the extent they stimulate the diffusion of clean technology. The interior equilibria serve as the indicator of this diffusion incentive since they measure the penetration of clean technology adopting firms. However, one can compare the equilibria based on two different bases. First, one can directly derive $\tilde{s}^k$ by solving $\Delta^k = 0$ without considering the environmental quality. Let us call these the unconstrained equilibria (UE). By evaluating diffusion incentives without explicitly considering a pollution target (like the UE), one can imagine that any degree of diffusion can be met as long as one sets the corresponding instrument variable (tax rate, subsidy rate, emission ceiling and emission standard) high enough. Determining which instrument yields the highest degree of diffusion is then quite arbitrary. Therefore, in order to provide a more correct basis for comparing the pollution control policies with each other, we first determine the diffusion equilibria given they all meet the same emission target in equilibrium; these are the so-called constrained equilibria (CE) $\bar{s}^k$. Subsequently, given the quality of the environment being equal under the four policy regimes, we can determine which policy yields the highest penetration of clean technology in the long run. Table 3 contains the formal expressions of both the UE and CE, where d_1, d_2 and

finds a unique interior solution iff $\frac{\beta}{\gamma} > \frac{\theta_d}{\theta_c}, \frac{\theta_c}{\theta_d}$. The first term on the right-hand-side should hold in the state $s = 0$. The reverse case applies in the state $s = 1$. This is reflected by the second term on the rhight-hand-side. The equation states that the industry converges to complete specialization in the clean good ($s = 1$) if $\beta/\gamma < \theta_c/\theta_d$, whereas all firms produce dirty goods ($s = 0$) if $\beta/\gamma < \theta_d/\theta_c$.

d_3 in the CE $\bar{s}^{cre}$ read as:

$$\begin{aligned} d_1 &= -(\zeta_c - \zeta_d)N(2(\beta-\gamma)E^* + \zeta_d\theta_c - (2\zeta_d - \zeta_c)\theta_d), \\ d_2 &= 4\beta(N+1)E^*\zeta_d\theta_d - (2(\beta-\gamma)E^* + \zeta_d\theta_c)(2E^*(\beta(N+2)+\gamma N)) + \zeta_c^2\theta_d^2 N, \\ d_3 &= 2\zeta_c(2\beta(N+1)E^*\theta_c - (2(\beta+\gamma N)E^* + \zeta_d\theta_c N)\theta_d). \end{aligned} \tag{10}$$

Table 3: Constrained and unconstrained diffusion equilibria

Policy	Unconstrained diffusion equilibria $\tilde{s}$	Constrained diffusion equilibria $\bar{s}$
Taxation	$\frac{\beta(N+1)(\theta_c-\tau\zeta_c)-(\gamma N+\beta)(\theta_d-\tau\zeta_d)}{(\beta-\gamma)N(\theta_d+\theta_c-\tau(\zeta_d+\zeta_c))}$	$\frac{\zeta_d(\zeta_d\theta_c N-(\beta+\gamma N)E^*)+\zeta_c(\beta(N+1)E^*-\zeta_d\theta_d N)}{N[\zeta_d((\beta-\gamma)E^*+\zeta_d\theta_c)+\zeta_c((\beta-\gamma)E^*-\zeta_d(\theta_c+\theta_d))+\zeta_c^2\theta_d]}$
Subsidies	$\frac{\beta(N+1)(\theta_c+\omega(\zeta_d-\zeta_c))-(\gamma N+\beta)\theta_d}{(\beta-\gamma)N(\theta_d+\theta_c-\omega(\zeta_c-\zeta_d))}$	$\frac{\beta(N+1)E^*-\zeta_d\theta_d N}{N((\beta-\gamma)E^*+(\zeta_c-\zeta_d)\theta_d)}$
Permits	$\frac{g[\beta(\zeta_d-\zeta_c(N+1))+\gamma\zeta_d N]+\zeta_d N(\theta_d\zeta_c-\theta_c\zeta_d)}{N[g(\gamma-\beta)(\zeta_d+\zeta_c)+(\zeta_d-\zeta_c)(\theta_d\zeta_c-\theta_c\zeta_d)]}$	$\frac{\zeta_d(\beta+\gamma N)E^*-\zeta_c\beta(N+1)E^*+\zeta_d N(\zeta_c\theta_d-\zeta_d\theta_c)}{N[(\zeta_d-\zeta_c)(\zeta_c\theta_d-\zeta_d\theta_c)-(\beta-\gamma)E^*(\zeta_d+\zeta_c)]}$
Credits	$\frac{\zeta_d-\delta}{\zeta_d-\zeta_c}$	$\frac{d_1\sqrt{(\zeta_c-\zeta_d)^2N(d_2+d_3)}}{2N(\zeta_c-\zeta_d)[(\zeta_c-\zeta_d)(\theta_c-\theta_d)-2(\beta-\gamma)E^*]}$

Table 4 shows the associated levels of the specific instruments that yield the CE as given in Table 3. The procedure for finding the CE and corresponding instrument levels as shown in Table 3 and 4 respectively is as follows. The first step is to fix an industry emission ceiling E^*, which is equal for all policy regimes. Then one needs to determine the associated instrument levels τ^*, ω^*, g^* and δ^* such that they all generate E^* in the CE ($\bar{s}^k$). The permit policy is the easiest case because by definition $g^* = E^*$. How to determine the levels τ^*, ω^* and δ^*? For this we make use of the UE as given in Table 3. We will illustrate the procedure for the taxation policy in order to find τ^*.

The same procedure can be applied to determine ω^* and δ^* for the subsidy and credit regime respectively.

Table 4: Pollution constrained instrument levels.

$$\tau^* = \frac{\beta(N+1)(\zeta_d\theta_d+\zeta_c\theta_c)-(\beta+\gamma N)(\zeta_d\theta_c+\zeta_c\theta_d)-(\beta-\gamma)E^*(\gamma N+\beta(N+2))}{\beta(N+1)(\zeta_c^2+\zeta_d^2)-2(\beta+\gamma N)\zeta_c\zeta_d}$$

$$\omega^* = \frac{\beta(N+1)(\zeta_d\theta_d+\zeta_c\theta_c)-(\beta+\gamma N)(\zeta_d\theta_c+\zeta_c\theta_d)-(\beta-\gamma)E^*(\gamma N+\beta(N+2))}{(\zeta_c-\zeta_d)[\beta(N+1)\zeta_c-(\beta+\gamma N)\zeta_d]}$$

$$g^* = E^*$$

$$\delta^* = \frac{\theta_c(\zeta_d^2-\zeta_c\zeta_d)+\theta_d(\zeta_c^2-\zeta_c\zeta_d)+2(\beta-\gamma)E^*+\sqrt{(\zeta_c-\zeta_d)^2N(d_2+d_3)}}{2N[2(\beta-\gamma)E^*-(\zeta_c-\zeta_d)(\theta_c-\theta_d)]}$$

By setting $s = \tilde{s}^{tax}$ without fixing τ, we obtain the unconstrained equilibrium $\tilde{s}^{tax}(\tau)$. Substituting $\tilde{s}^{tax}$ into the model, all variables become dependent on τ and E^{tax}. The only thing we have to do now is to solve $E^{tax} = E^*$ for τ, in order to find τ^*. Substitution of τ^* back into $\tilde{s}^{tax}$ yields the constrained diffusion equilibrium $\bar{s}^{tax}$; the stable diffusion state at which industry emissions are equal to the emission ceiling E^*. In the same way ω^* and δ^* and subsequently $\bar{s}^{sub}$ and $\bar{s}^{cre}$ can be found.

5 Instrument ranking

The ranking of the four policy instruments on the basis of diffusion incentives can simply be done by comparing the four CE given in Table 3 and determine which one is bigger to the other. This leads us to the following proposition:

Proposition 1 *In a differentiated market with products being imperfect substitutes ($\beta > \gamma$ but $\alpha_d \neq \alpha_c$), the ranking order of the constrained diffusion equilibria CE reads:*

$$\bar{s}^{tax} = \bar{s}^{per} \gtreqless \bar{s}^{cre} \gtreqless \bar{s}^{sub} \Longleftrightarrow h_1\theta_c - h_2\theta_d \lesseqgtr a,$$

where

$$\begin{aligned} h_1 &= \beta(N+1)\zeta_c - (\beta + \gamma N)\zeta_d \lesseqgtr 0, \\ h_2 &= (\beta + \gamma N)\zeta_c - \beta(N+1)\zeta_d < 0, \\ a &= (\beta - \gamma)(\gamma N + \beta(N+2))E^* > 0. \end{aligned}$$

Proof. The instruments are compared analytically in pairs. That is, we determined analytically when $\bar{s}^{tax} - \bar{s}^{sub} \lesseqgtr 0$, then $\bar{s}^{tax}$ versus $\bar{s}^{cre}$ and so on.[7] By evaluating in this way the common parameters h_1, h_2 and a are found. It is then straightforward to obtain the ranking. ■

Provided that $\beta > \gamma$, we find $a > 0, h_1 \gtreqless 0, h_2 < 0$ and $h_1 > h_2$. Proposition 1 states that emission taxes and permits provide equal diffusion incentives. It then follows directly that $\tau^* = \bar{\sigma}$, which can be checked by substituting the CE $\bar{s}^{per}$ into the permit price function (7).

What does proposition 1 imply? In the first place that the ranking depends strongly on the underlying market structure in terms of the degree of product differentiation (measured by the difference between β and γ). Moreover, it depends on whether the clean or dirty firm has a net absolute advantage (θ_j), which is conditional on the demand structure measured by α_j and variable costs ϑ_j. Finally, it depends on the

[7] Because of the nasty analytical expressions, this is done by using the mathematical software package *Mathematica*.

relative pollution intensiveness of the clean and dirty technology (ζ_c versus ζ_d). So by implementing the "right" policy instrument in order to establish the highest degree of clean technology diffusion, the policy maker has to take into account the market structure, costs, and the relative pollution intensiveness of the technologies.

Based on proposition 1 it can be shown how the ranking order is affected by a change in the degree of product substitutability. To illustrate how a switch in ranking may be established suppose now that the products are perfect substitutes, i.e., $\beta = \gamma$. Consequently:

Corollary 2 *In a differentiated market with products being perfect substitutes* ($\beta = \gamma$, *but* $\alpha_d \neq \alpha_c$), *the ranking order of the constrained diffusion equilibria CE reads:* $\bar{s}^{tax} = \bar{s}^{per} \gtreqless \bar{s}^{cre} \gtreqless \bar{s}^{sub} \Longleftrightarrow \theta_d \lesseqgtr \theta_c$.

Proof. If $\beta = \gamma$, it follows directly that $a = 0$ and $h_1 = h_2 = h < 0$. Substituting this into the ranking rule of proposition 1, we obtain $h(\theta_c - \theta_d) \lesseqgtr 0$. Since $h < 0$ $\Longrightarrow h\theta_d \lesseqgtr h\theta_c \Longleftrightarrow \theta_d \lesseqgtr \theta_c$. ■

Corollary 2 states that when products are perfect substitutes and, moreover, the clean firm has a net absolute advantage over the dirty firm ($\theta_d < \theta_c$), permits and taxes provide the highest penetration of clean technology followed by credits and subsidies respectively. When the reverse holds – the dirty firm faces a net absolute advantage which is higher than the clean firm's advantage ($\theta_d > \theta_c$) – the subsidy instrument switches with permits and taxes, whereas credits maintains its second rank.

Why is it that subsidies provide the highest diffusion incentive in case $\theta_d > \theta_c$? Because in such a case dirty firms have a net absolute advantage over clean firms, potential profits also tend to be higher for dirty firms relative to clean firms. We have seen that an emission reduction subsidy does not increase the price of dirty output directly, but only indirectly by decreasing the price of the clean good. Since lower prices stimulate demand, total output tends to increase. Consequently, the emission target E^* can then only be reached by a relatively deep penetration of clean technology. To put it differently. When $\theta_c > \theta_d$, there already exists a positive incentive to switch from the dirty to the clean technology. Now the subsidy does not have to be as high as when $\theta_d > \theta_c$, where the imposed subsidy has to generate an *extra* incentive in order to meet the emission target E^*.

A second corollary that can be derived in a straightforward manner from proposition 1 concerns the fully homogeneous market structure. Compared to the previous case (the direct and cross price effect being equal), now also no difference in the price intercepts α exists, i.e., $\alpha_d = \alpha_c$. That is,

Corollary 3 *In a full homogeneous market ($\beta = \gamma$ and $\alpha_d = \alpha_c$), the ranking order of the constrained diffusion equilibria CE reads:* $\bar{s}^{tax} = \bar{s}^{per} > \bar{s}^{cre} > \bar{s}^{sub}$.

Proof. If $\beta = \gamma$, it follows directly that $a = 0$ and $h_1 = h_2 = h < 0$. Substituting this into the ranking rule of proposition 1, we obtain $h(\theta_c - \theta_d) = 0$. Moreover, $\alpha_d = \alpha_c = \alpha$. Writing out θ_j according to equation (4), $h(\theta_c - \theta_d) = h(\alpha - \vartheta_c - \alpha + \vartheta_d) = h(\vartheta_d - \vartheta_c) < 0$ because $h < 0$ and $\vartheta_d > \vartheta_c$. The ranking order then follows straightforwardly from proposition 1. ■

Table 5 summarizes the relative ranking orders for the above distinguished market cases. Rank number "1" means that the instrument stimulates diffusion most, i.e., it leads to the highest penetration of clean technology. As discussed above, Table 5 shows that the ranking is ambiguous under a heterogeneous market structure given the degree of product substitutability. It contains the explicit mathematical conditions for which the instruments switch positions. In case the market is fully homogeneous, the ranking order is unambiguous and permits and taxes do always generate the highest diffusion incentives followed by credits and subsidies respectively.

Table 5: Ranking order constrained diffusion equilibria under different market settings

Policy	Heterogeneous market		Homogeneous market
	Imperfect substitutability	Perfect substitutability	
	$h_1\theta_c - h_2\theta_d < (>)\ a$	$\theta_d < (>)\ \theta_c$	
Taxation	1 (3)	1 (3)	1
Permits	1 (3)	1 (3)	1
Credits	2 (2)	2 (2)	2
Subsidies	3 (1)	3 (1)	3

Let us also put the ranking results derived above into a welfare context. The idea behind welfare maximization is that production is expanded as long as it generates additional positive welfare. Welfare maximization in relation to an environmental policy burden implies stimulating production with a limit on total allowed emissions.

As is well known, maximum welfare can be realized by either a full informed perfect planner or by a market system characterized by perfect competition. Moreover, it is also well known that generally oligopolistic markets generate output levels that are too low compared to the welfare maximum. Combining these two results, the major force in explaining the differences is the impact of the instruments on total output and its composition (clean versus dirty), given the specified market conditions. Emission reduction subsidies stimulate clean production without directly discouraging dirty production. Consequently, higher total output, which tends to push up emissions, requires a relatively deep penetration of clean technology and a higher share of clean output.

The story for taxes and permits goes the other way around. By putting a price on emissions, firm-level output is negatively affected and will therefore generate lower total output, hence yielding fewer emissions. In terms of diffusion, this implies that the industry does not have to be as "clean" as under a subsidy regime.

Like taxes and permits, a credit scheme attaches a price to emissions too, but only to the emissions of dirty firms that exceed the emission standard. If costs of credits depress output less than the tax and permit regime do, it requires a somewhat higher degree of clean technology diffusion.

To summarize, the results of this paper indicate that in oligopolistic markets the implementation of emission taxes and permits tend to restrict the supply of both clean and dirty output even further. If the market structure would have been perfectly competitive, the negative impact on output would have been optimal because it prevents output from being too high given the shadow price of emissions. However, in case output supply is already too low due to oligopolistic forces, permits and taxes work in the wrong direction. In such a case, subsidies are the appropriate instrument since they stimulate output supply positively. Tradable credits lower the price of clean output but raise the price of dirty output. Its impact on output is therefore in between the impacts of permits/taxes and subsidies.

6 Conclusions

We ranked and evaluated emission taxes, emission reduction subsidies, tradable emission permits, and tradable emission credits on the criterion of technology diffusion incentives. In order to avoid an arbitrary comparison, we introduced an emission target which is equal for all the four control policies. For each instrument we subsequently determined the so-called "constrained equilibrium" (CE), which is the equilibrium diffusion state that satisfies the emission target. The CE is thus a direct measure of the diffusion incentive given a fixed industry emission ceiling. Emission taxes and permits provide equivalent diffusion incentives and the emission tax coincides with the permit price in the diffusion equilibrium under permits.

Comparing the diffusion incentives under the four policies learns that no unique instrument ranking exists in a differentiated market. When products are imperfect substitutes, the ranking order depends on the on the market (demand) structure, cost structure, and the technologies' relative pollution intensiveness. If products are perfect substitutes, the ranking order depends on the demand and cost structure. More specifically, if in such a case the clean firm has a net absolute advantage over the dirty firm then (1) permits and emission taxes provide the highest diffusion incentive, followed by (2) credits, and (3) subsidies. This order is completely reversed if the dirty firm faces a net absolute advantage over the clean firm. Under a homogeneous market setting, the ranking order is, however, unambiguous. The relative performance on the basis of diffusion incentives is then: (1) permits and emission taxes, (2) credits, and (3) subsidies.

The ranking order can be reversed with product heterogeneity and a stronger distortion due to oligopoly. In case of such a strong oligopolistic market structure, the analysis suggests a second-best policy. A distorting environmental policy instrument like emission reduction subsidies can be applied to redress the distortion created by the oligopolistic market structure. This redress consists of stimulating output, which is held back by profit maximizing oligopolistic firms; there is a boost from the emission reduction subsidy, which indirectly stimulates the demand for products that are manufactured in an environmentally friendly manner.

Appendix

First-order conditions

Table 6:

Policy	$\partial\pi_j^k/\partial q_j^k = 0 \ (j = d, c)$
Laissez faire	$\theta_j - \beta(\widehat{X}_j^{lf} + x_j^{lf}) - \gamma X_{-j}^{lf} - \beta x_j^{lf} = 0$
Taxation	$\theta_j - \tau\zeta_j - \beta(\widehat{X}_j^{tax} + x_j^{tax}) - \gamma X_{-j}^{tax} - \beta x_j^{tax} = 0$
Subsidies	$\theta_d - \beta(\widehat{X}_d^{sub} + x_d^{sub}) - \gamma X_c^{sub} - \beta x_d^{sub} = 0$ $\theta_c + \omega(\zeta_d - \zeta_c) - \beta(\widehat{X}_c^{sub} + x_c^{sub}) - \gamma X_d^{sub} - \beta x_c^{sub} = 0$
Permits	$\theta_j - \sigma\zeta_j - \beta(\widehat{X}_j^{per} + x_j^{per}) - \gamma X_{-j}^{per} - \beta x_j^{per} = 0$
Credits	$\theta_j - \phi(\zeta_d - \delta) - \beta(\widehat{X}_j^{cre} + x_j^{cre}) - \gamma X_{-j}^{cre} - \beta x_j^{cre} = 0$

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