Discussion Papers No. 371, March 2004
Statistics Norway, Research Department

Mads Greaker

Industrial Competitiveness and Diffusion of New Pollution Abatement Technology – a new look at the Porter-hypothesis

Abstract:
We study the relationship between industrial competitiveness, adaption of cleaner production techniques and environmental policy. While other contributions have analyzed environmental innovations with point of departure in the polluting firm, we introduce an up-stream market for new pollution abatement technology. A strong environmental policy may then benefit industrial competitiveness through its effect on the price on pollution abatement. However, the incentive for a stringent policy partly disappears if there is a global market for pollution abatement solutions, and environmental policy is set simultaneously in several countries.

In our analysis we hope to draw attention to an often overlooked issue. The diffusion of new pollution abatement techniques often requires a new market to develop. If policy is lax, few firms enter and may charge a high mark-up to cower entry costs. On the other hand, a stringent environmental policy induces higher demand and allows a lower mark-up. Consequently, even if the polluting industry in question is export oriented, a stringent policy may be welfare enhancing.

Keywords: Strategic Environmental Policy, Eco-dumping, Porterhypothesis

JEL classification: H7; Q2; R3

Address: Mads Greaker, Statistics Norway, Research Department. E-mail: mgr@ssb.no

Discussion Papers comprise research papers intended for international journals or books. As a preprint a Discussion Paper can be longer and more elaborate than a standard journal article by including intermediate calculation and background material etc.

Abstracts with downloadable PDF files of
Discussion Papers are available on the Internet: http://www.ssb.no

For printed Discussion Papers contact:

Statistics Norway
Sales- and subscription service
N-2225 Kongsvinger

Telephone: +47 62 88 55 00
Telefax: +47 62 88 55 95
E-mail: Salg-abonnement@ssb.no

1 Introduction.

Trade liberalization, will according to the popular view, shift power from governments to firms and make it easier for firms to resist costly environmental regulation by referring to their need to stay competitive. However, this argument only holds to the extent that tough environmental regulation hurts competitiveness, and so long as governments respond to reduced competitiveness by setting a less stringent environmental policy. According to Porter [17] and to Porter and Linde [18] governments can tighten their level of environmental regulation, and firms will find that they become more competitive, not less. This has come to be coined the Porter-hypothesis.

The Porter-hypothesis may be given at least two different interpretations. According to Porter and Linde [18] emissions are signs of inefficiencies, that is, "material" is wasted and not used for any "purpose". Removing emissions will therefore lead to efficiency improvements in the form of less "material usage" per unit of the final product. Thus, in its strong form the hypothesis basically says that firms will save costs on environmental regulation, and that no weighting of abatement costs and environmental benefits are necessary.

On the other hand, the Porter-hypothesis was first introduced as a response to the claim that US firms had become less competitive due to stringent environmental regulation during the the 1980's. According to Porter [17] the critics were wrong, and the right form of more stringent regulation could spur international competitiveness[1]. A possible weak interpretation of the Porter-hypothesis is then that a tough environmental policy makes firms more internationally competitive than a weak environmental policy.[2]

There exists a well developed strand of theoretical literature analyzing the relationship between competitiveness and environmental policy, see for instance Barrett [1], Conrad [5], Kennedy [15], Rauscher [19], Bradford and Simpson [2], Ulph and Ulph[23] and Ulph[22]. This literature looks at oligopolistic export industries in which firms earn pure profit. For such industries marginal cost can be used as a measure of "competitiveness" (see Tirole [21], chapter 8). However, in many of the contributions it is preassumed that environmental policy increases marginal costs, and the focus is instead solely on the choice of environmental policy, see for example Barrett [1] and Rauscher [19].

Ulph [24] extends the basic model and covers research and devel-

[1] We will not venture into this part of the discussion here, but just mention that Porter called for market based incentives instead of technology standards etc.

[2] Se Jaffe et al.[13] for more interpretations.

opment of new, less polluting processes, partly in order to investigate issue of competitiveness and the Porter-hypothesis more closely[3]. For one version of the model in Ulph [24] a stringent environmental policy leads to more competitive firms, that is, a higher emission tax makes marginal cost decrease. The reason is that emissions per unit of output falls due to the increased R&D effort, and that this effect dominates the direct effect of the higher tax. However, the extent to which governments should set a high emission tax in order to exploit this relationship remains ambiguous.

Greaker [9] also provides results which are related to the Porter-hypothesis. It is known from production theory that if an input is inferior, marginal costs decrease when the price of the input increases (see for example Gravelle and Rees [8]). Hence, to the extent that emissions are inferior inputs, marginal cost could be decreasing in an emission tax if you go from a situation with a low tax rate to a situation with a high tax rate. This is studied in Greaker [9], and an analytical model based on case studies suggests that emissions may be an *inferior* input to the extent that abatement technology has scale advantages. It is further shown that governments should exploit this in a strategic trade setting, and set a high emission tax to take advantage of the scale property.

In this paper we will look at another possible explanation behind the weak interpretation of the Porter-hypothesis. In the contributions mentioned above, and in most other analyses, the point of departure is that the development of new pollution abatement techniques happens within the polluting firm [4]. The analysis of environmental policy versus competitiveness may then miss an important aspect. Take for example the U.S. SO_2 cap and trade program. According to Burtraw and Palmer [4], the main savings from the program were due to increased competition between abatement suppliers, and not from differing abatement costs among polluters.

When regulation changed from a technology standard to tradable emission quotas, upstream industries such as railroad transportation, scrubber manufacturing and coal mining companies were thrown into competition with each other in a race to supply the electricity generating industry with low cost compliance strategies. This lead the price of low sulphur coal to fall by 9% even though total supply increased by 28%. Further, coal transportation prices fell from 20-26 mills (one mill is one tenth of a cent) per ton-mile to 10-14 mills per ton-mile. Lastly, the efficiency of scrubbers was enhanced, leading to a drop in the price of

---

[3] Bradford and Simpson [2], Ulph and Ulph[23] and Ulph[22] include similar models.

[4] See also Downing and White[6] and Jung, Krutilla and Boyd[14].

scrubbing measured as emission reduction per $.

Hence, we look at the relationship between competitiveness and environmental policy in a model in which the supply of *pollution abatement services* takes place in an imperfectly competitive *upstream* market. In particular, we show that a tough environmental policy may improve downstream competitiveness. A strong environmental policy increases entry into the industry providing abatement services. This lowers the price on pollution abatement and may consequently make the polluting industry increasingly competitive. Accordingly, the government should set an especially stringent environmental policy. On the other hand, the incentive to set a stringent policy partly disappears if there is a global market for pollution abatement services, and environmental policy is set simultaneously in several countries.

The analysis also includes some other potentially interesting insights. Firstly, we show that a stringent environmental policy could be recommended even though competitiveness is hurt by a stringent environmental policy. The fact that the price of pollution abatement is decreasing in the stringency of the environmental policy instrument both reduces the strategic disadvantage of a stringent environmental policy, and provides a separate incentive for setting a stringent policy. The extent to which there already exists a well developed market for abatement services is thus of high importance to the policy maker. Secondly, the availability of an abatement subsidy does not necessarily change this result; environmental policy should be still be stringent if environmental policy spurs competitiveness.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 to Section 5 presents the general results of the model. All results are then illustrated by the use of examples in Section 6 and Section 7. Section 8 looks at additional policy instruments, that is, two kinds of subsidies. Section 9 concludes and offers some suggestions for further research.

2 The model

The model is an extension of the model in Ulph[24], and involves two industries located in two separate countries referred to as the *domestic* and the *foreign* country. Both the domestic and the foreign industry sells its output in the same common market, and pollutes its local environment. The domestic and foreign government regulate their industries by setting local emission quotas $\bar{e}$ and $\bar{E}$, respectively. The industries take the emission quotas as given, and demand pollution abatement services from an engineering sector in each country or one common i.e. trade with pollution abatement services. The category *pollution abatement* *services* is defined broadly. That is, in order to reduce emissions the downstream industry may have to implement a new process developed by the abatement sector, or invest in new pollution abatement equipment, or change to some new sort of raw materials, both supplied by the upstream firms. Finally, the two polluting industries compete in Cournot fashion by choosing their level of output.

In order to simplify, we focus on a single duopoly downstream with only one domestic firm and one foreign firm. However, one can think of both the domestic and the foreign downstream industry as consisting of many firms, emitting the same type of pollutant, but competing on *different* duopoly markets outside both countries. According to the World Bank Pollution Abatement Handbook[25] firms from *different* industries often have *similar* pollution abatement needs. For instance, electrostatic precipitators removing particles are sold to a whole range of different industries. The important assumption is that no single firm has monopsony power in the market for pollution abatement services.

We start by analyzing the unilateral game. In this game only the domestic government sets an emission quota, while the foreign government is passive. Consequently, a market for pollution abatement solutions only develops in the domestic country.

2.1 The pollution abatement technology

In order to comply with future environmental regulations the representative downstream polluting industry buys pollution abatement services from the upstream engineering sector. Denote the extent to which an abatement solution is implemented by x. Emissions, s, from the downstream industry is then given:

$$s = f(x, q), \tag{1}$$

where q is output. The f function has the following derivatives: $f_q > 0$, $f_x \leq 0$, $f_{xx} > 0$. The sign on the second order derivative f_{xx}implies that there are diminishing returns to abatement effort.

In the first stage of the unilateral game the domestic government sets an emission quota $\bar{e}$, which implies $s \leq \bar{e}$. The foreign government has no environmental policy, and sets no particular emission quota. The domestic firm invests in abatement effort exactly up to the level for which the emission quota bites, which implies; $f(x, q) = \bar{e}$. The abatement effort can then be written; $x = x(q, \bar{e})$. It is easy to check that $x_{\bar{e}} \leq 0$ and that $x_q \geq 0$. We assume that $x_{q\bar{e}} < 0$ in order to ensure that emissions are normal inputs.[5]

[5]Emission may be inferior, see Greaker [9] for a discussion and analysis of emissions

The downstream cost of abatement effort is given by: wx (price w times quantity x):

$$c(q, \bar{e}) = wx(q, \bar{e}). \tag{2}$$

In the following we normalize all other costs of the downstream firm to zero. We can then solve the game by backwards induction, and start by looking at the third stage of the game:

2.2 The downstream export market

Let Q denote the output of the foreign downstream firm. Total revenues of the domestic and the foreign firms are then $y(q, Q)$ and $Y(q, Q)$, respectively. For the derivatives of the revenue functions , we have $\frac{\partial y}{\partial Q}, \frac{\partial Y}{\partial q} < 0$, meaning that the products are substitutes, and $\frac{\partial^2 y}{\partial Q \partial q}, \frac{\partial^2 Y}{\partial q \partial Q} < 0$, meaning that outputs are strategic substitutes.

With domestic costs equal to $wx(q, \bar{e})$, and foreign costs normalized to zero, the two first order conditions for profit maximum write:

$$\partial \pi / \partial q = \frac{\partial y}{\partial q} - wx_q = 0, \tag{3}$$

and

$$\partial \Pi / \partial Q = \frac{\partial Y}{\partial Q} = 0. \tag{4}$$

The two first-order conditions determine the Nash-equilibrium output quantities given the domestic emission quota. Assuming that the second-order conditions for profit maximum hold, and that the uniqueness condition for the Nash equilibrium is met[6], output quantities can be written as; $q = q(w, \bar{e}))$ and $Q = Q(w, \bar{e})$. It is further easy to show that we have:

$$\frac{dq}{d\bar{e}\,|_{\frac{dw}{d\bar{e}}=0}} > 0 \text{ and } \frac{dq}{dw} < 0, \tag{5}$$

$$\frac{dQ}{d\bar{e}\,|_{\frac{dw}{d\bar{e}}=0}} < 0 \text{ and } \frac{dQ}{dw} > 0. \tag{6}$$

(See Appendix A1 for a complete derivation of the Nash equilibrium and the comparative statics results).

Since the foreign downstream firm is not obliged to do abatement, a price increase on pollution abatement only affects the domestic firm negatively. On the contrary, the foreign firm benefits, since in the new Nash equilibrium, profit is shifted towards the foreign firm.

---

as inferior/normal inputs. In the current paper we confine the analysis to emissions as normal inputs.

[6] See the discussion about uniqueness in Tirole[21], page 225-226.

2.3 The upstream pollution abatement market

In order to start supplying pollution abatement services, the engineering firm has to obtain basic knowledge and experience about possible approaches to the pollution problem at hand, and/or license a particular technology from an inventor. This implies some fixed costs of setting up a pollution abatement firm. Clearly, there may be positive externalities between pollution abatement firms; for instance, a knowledge base may be easier to obtain if there are more firms working on the same problem. One way of modelling this is to let the fixed entry cost be decreasing in the number of upstream firms. This is also another way of saying that firms can (imperfectly) imitate each other's approaches (see Haaland and Wooton[10] for a similar approach).

Having solved for downstream output above, we may write total demand for pollution abatement solutions, x:

$$x = x(q(w, \bar{e}), \bar{e}), \tag{7}$$

which can be inverted to a demand function for pollution abatement services:

$$w = w(\bar{e}, x). \tag{8}$$

Differentiating (7) we get:

$$\frac{dw}{dx} = \frac{1}{x_q \frac{dq}{dw}} < 0, \tag{9}$$

that is, the demand function is downward sloping.

At any time, there are n firms in the pollution abatement sector. Competition in the sector is modelled as Cournot-Nash with free entry. Even though we assume that the engineering firms offer perfect substitutes, this does not necessarily imply that they offer identical technologies, but only that the different technologies are equally efficient with respect to emission abatement.

Denote the variable cost of supplying abatement solutions α, and denote the fixed cost of entering the abatement effort marked by $f = f(n)$ with $f' \leq 0$, and $\frac{d[nf(n)]}{dn} = f(n) + nf' > 0$, i.e. the sum of entry costs is increasing in n. Each abatement firm then maximizes profit Ω taking $\bar{e}$ and n as given:

$$\max_{x_i} \left[w(\bar{e}, \sum_{i=1}^{n} x_i) - \alpha \right] x_i - f(n), \tag{10}$$

Assuming that upstream firms are symmetric, and solving this problem, we get: $x_1 = ... = x_i = ... = x_n = \bar{x}(n, \bar{e})$. We may then find n

from:

$$\Omega_i = [w(\bar{e}, n\bar{x}(n,\bar{e})) - \alpha]\,\bar{x}(n,\bar{e}) - f(n) = 0, \tag{11}$$

which yields: $n = n(\bar{e})$. Total supply of pollution abatement can then be written; $x = n(\bar{e})\bar{x}(n(\bar{e}), \bar{e})$. Inserting the expression $n(\bar{e})\bar{x}(n(\bar{e}), \bar{e})$ back into the expression for the price, we finally get $w = w(\bar{e}, n(\bar{e})\bar{x}(n(\bar{e}), \bar{e})) = w(\bar{e})$.

In the general case, the sign on the derivative $\frac{dw}{d\bar{e}}$ is ambiguous. In Appendix C1 and C4 we solve the model for a linear export demand function and the following emission function; $f(x,q) = (\frac{\upsilon}{\sigma x + \mu})q$ where υ, σ, μ are parameters, and find that $\frac{dw}{d\bar{e}} > 0$ independent of the existence of positive externalities between abatement firms i.e. $f'(n) = 0$. We also solve the model for a proportional emission standard, linear export demand and the following emission function: $f(x,q) = q - \sqrt{qx}$. Again, we find that $\frac{dw}{d(1-r)} > 0$ for $f'(n) = 0$, where $(1-r)$ is maximum emissions per unit of output. See also Appendix B for further details.

3 Competitiveness and environmental policy

As already argued, we associate *competitiveness* with the level of marginal cost $wx_q(q, \bar{e})$. If marginal cost decreases with a tightening emission quota, competitiveness is improving in the stringency of environmental policy as predicted by the Porter-hypothesis. The following proposition states the necessary and sufficient conditions for this to happen:

Proposition 1 *Competitiveness is improving when the emission quota is tightened if and only if $\frac{\partial w}{\partial \bar{e}}x_q > |wx_{q\bar{e}}|$. Hence, a necessary condition is $\frac{dw}{d\bar{e}} > 0$.*

A smaller emission quota has two effects: Firstly, it increases marginal cost through the term $x_{q\bar{e}}$, that is, for each additional increase in output, the firm has to do more pollution abatement the smaller the emission quota. Secondly, it may lower the price on environmental R&D. This makes abatement less costly, which may completely outweigh the first effect.

The condition$\frac{\partial w}{\partial \bar{e}}x_q > |wx_{q\bar{e}}|$, results in a weak form of the Porter-hypothesis:

Proposition 2 *In the unilateral policy case, if $\frac{\partial w}{\partial \bar{e}}x_q > |wx_{q\bar{e}}|$, export output improves when the emission quota is tightened, that is, $\frac{dq}{d\bar{e}} < 0$.*

Proof. See Appendix A1. ■

In an example below, we show that positive externalities between pollution abatement firms, mean that the domestic government can demand higher emission reductions, and at the same time increase export output.

4 Optimal domestic emission quota

Our benchmark is the first-best rule for optimal environmental policy i.e. *marginal abatement cost* should equal *marginal environmental damage*. If the welfare maximizing environmental policy in the unilatteral game diverts from the first best rule, we will say that environmental policy is *lax/stringent* depending on whether *marginal abatement cost* is lower/higher than *marginal environmental damage*.

Welfare is given by the net surplus NS generated by the domestic downstream firm:

$$NS = y(q(w(\bar{e}), \bar{e}), Q(w(\bar{e}), \bar{e})) - w(\bar{e})x(q(w(\bar{e}), \bar{e}), \bar{e}) - d(\bar{e}), \qquad (12)$$

where the two first terms is the profit of the firm and the last element $d(\bar{e})$ is an environmental damage function with $d' > 0$, $d'' \geq 0$.

Note that the upstream market is not a part of the expression, since there is zero profit in the sector. The revenue generated in this sector is equal to total R&D cost, which again is equal to the total amount of resources consumed by the sector.

Denote the derivative $\frac{dq}{d\bar{e}}_{|\frac{dw}{d\bar{e}} \neq 0}$ by just $\frac{dq}{d\bar{e}}$, and denote $x(q(w(\bar{e}), \bar{e}), \bar{e})$ by $x(q, \bar{e})$. The first order condition for maximizing net surplus then becomes:

$$\frac{dNS}{d\bar{e}} = [y_q - w(\bar{e})x_q] \frac{dq}{d\bar{e}} + y_Q \frac{dQ}{d\bar{e}} - \frac{\partial w}{\partial \bar{e}} x(q, \bar{e}) - w(\bar{e})x_{\bar{e}} - d' = 0, \qquad (13)$$

where the first term is zero by the first order condition for profit maximum (see Appendix A1). By rearranging terms and using that $\frac{dQ}{d\bar{e}} = \frac{\partial Q}{\partial w} \frac{dw}{d\bar{e}} + \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0}$, we get:

$$y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0} + \left[y_Q \frac{\partial Q}{\partial w} - x(q, \bar{e}) \right] \frac{dw}{d\bar{e}} = - |w(\bar{e})x_{\bar{e}}| + d'. \qquad (14)$$

The left hand side presents the "external" effects of environmental regulation, that is, the strategic effect $y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0}$ and an abatement price effect; $\left[y_Q \frac{\partial Q}{\partial w} - x(q, \bar{e}) \right] \frac{dw}{d\bar{e}}$.

While the strategic effect is discussed extensively in the literature, the price effect has not been discussed before. To the extent that $\frac{dw}{d\bar{e}} > 0$, the price effect works in two ways, which both tends to make environmental policy more stringent. Firstly, the term $y_Q \frac{\partial Q}{\partial w}$ provides another strategic effect, that is, when the price on pollution abatement falls, the foreign firm is affected negatively, and profit is shifted towards the domestic firm.

Secondly, the price effect has a direct cost-reducing effect on pollution abatement by $-x(q,\bar{e})$.

The term $\left|w(\bar{e})\frac{dx}{d\bar{e}}\right|$ at the right hand side represents marginal abatement cost, while the term d' is marginal environmental damage (henceforth; *mac.* and *med.*, respectively). Thus, the first best rule implies $-\left|w(\bar{e})\frac{dx}{d\bar{e}}\right| + d' = 0$.

Denote the right and left hand side of (14) by HS and LS, respectively. We then have the following proposition:

Proposition 3 *Environmental policy should be either stringent or lax according to:*

1. *If* $\frac{\partial w}{\partial \bar{e}} > 0$,*and if* $y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0} < \left|\left[y_Q \frac{\partial Q}{\partial w} - x(q,\bar{e})\right] \frac{dw}{d\bar{e}}\right|$, *that is, the* price effect *dominates the* strategic effect, LS is negative, *and* HS *must be negative. Hence, the government should set a stringent environmental policy.*

2. *If* $\frac{\partial w}{\partial \bar{e}} > 0$,*and if* $y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0} > \left|\left[y_Q \frac{\partial Q}{\partial w} - x(q,\bar{e})\right] \frac{dw}{d\bar{e}}\right|$, *that is, the* strategic effect *dominates the* price effect, LS is positive, *and* HS *must be positive. Hence, the government should set a lax environmental policy.*

3. *Lastly, if* $\frac{\partial w}{\partial \bar{e}} \leq 0$, LS *is always positive. The government should then set a lax environmental policy.*

Note that $\frac{dq}{d\bar{e}}_{|\frac{dw}{d\bar{e}}\neq 0} < 0$ is not a necessary condition for environmental policy to be stringent. The intuition is that an undeveloped market for new pollution abatement techniques requires a more stringent environmental policy in order to develop, and spur the diffusion of the new techniques. This incentive may be so strong that the government actually ends up setting a *stringent* environmental policy independent of the effect on competitiveness.

On the other hand, $\frac{dq}{d\bar{e}}_{|\frac{dw}{d\bar{e}}\neq 0} < 0$ is a sufficient condition for environmental policy to be stringent. In the latter case we have $y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0} < \left|y_Q \frac{\partial Q}{\partial w} \frac{dw}{d\bar{e}}\right|$, and the condition $y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0} < \left|\left[y_Q \frac{\partial Q}{\partial w} - x(q,\bar{e})\right] \frac{dw}{d\bar{e}}\right|$ is automatically fulfilled.

5 The policy game

We now turn to the policy game, and assume that the domestic and foreign governments set their emission quotas simultaneously. There are at least two options with respect to how the upstream market for pollution abatement services should be treated. One could think of situations in which supplying pollution abatement services required closeness to the polluting firms. Consequently, separate upstream sectors would develop in the two countries, and the price of pollution abatement services could differ between the upstream markets. Alternatively, abatement services could be tradable crossboarders. Hence, the price on pollution abatement service would be equalized between the two countries. We start looking into this latter option.

Assume that the downstream firms are symmetric, and let the foreign emission quota be denoted $\bar{E}$. The foreign demand for pollution abatement solutions can then be written; $X = X(Q, \bar{E})$, and the foreign cost function $C(Q, \bar{E}) = wX(Q, \bar{E})$ where the price on pollution abatement solutions w is the same for both downstream firms.

The third stage Nash equilibrium output quantities can then be written as; $q = q(w, \bar{e}, \bar{E}))$ and $Q = Q(w, \bar{e}, \bar{E})$. Further, it is easy to show:

$$\frac{dq}{d\bar{e}}_{|\frac{dw}{d\bar{e}}=0} > 0 \text{ and } \frac{dq}{dw}_{|\bar{e}=\bar{E}} < 0, \tag{15}$$

$$\frac{dQ}{d\bar{E}}_{|\frac{dw}{d\bar{e}}=0} > 0 \text{ and } \frac{dQ}{dw}_{|\bar{e}=\bar{E}} < 0. \tag{16}$$

Note that the signs on $\frac{dq}{dw}$ and $\frac{dQ}{dw}$ are both ambiguous; it is only when $\bar{e} = \bar{E}$ that the derivatives can be signed. Since both firms are supposed to do pollution abatement, a price increase on abatement negatively affects both firms. If one of the firms is required to do very little abatement compared to the other firm, the signs on the derivatives may differ, though. (See Appendix A2 for a derivation of the the comparative statics results).

Total demand for abatement services is then:

$$Z = x(q(w, \bar{e}, \bar{E}), \bar{e}) + X(Q(w, \bar{e}, \bar{E}), \bar{E}). \tag{17}$$

Z can be inverted:

$$w = w(\bar{e}, \bar{E}, Z).$$

The Cournot-Nash, free-entry equilibrium in the upstream market can then be found as above, and the price on environmental R&D can finally be written; $w = w(\bar{e}, \bar{E})$.

Net surplus NS generated by the domestic and foreign downstream firms, respectively, are:

$$NS_d = y(q(w(\bar{e}, \bar{E}), \bar{e}, \bar{E}), Q(w(\bar{e}, \bar{E}), \bar{e}, \bar{E})) \tag{18}$$

$$-w(\bar{e},\bar{E})x(q(w(\bar{e},\bar{E}),\bar{e},\bar{E}),\bar{e})-d(\bar{e}),$$

$$NS_f=Y(q(w(\bar{e},\bar{E}),\bar{e},\bar{E}),Q(w(\bar{e},\bar{E}),\bar{e},\bar{E})) \tag{19}$$

$$-w(\bar{e},\bar{E})X(Q(w(\bar{e},\bar{E}),\bar{e},\bar{E}),\bar{E})-d(\bar{E}),$$

where subscript d denote domestic and subscript f denote foreign.

The first order conditions for maximizing domestic and foreign net surplus imply $\frac{dNS_d}{d\bar{e}}=\frac{dNS_f}{d\bar{E}}=0$. We assume that the policy equilibrium is unique. Since the countries and firms are symmetric, the policy equilibrium must be symmetric. Hence, we only need to look at one of the first order conditions, and use that $\bar{e}=\bar{E}$ in equilibrium After some rearranging we get:

$$y_Q\frac{\partial Q}{\partial \bar{e}}_{\left|\frac{dw}{d\bar{e}}=0\right.}+\left[y_Q\frac{\partial Q}{\partial w}_{\left|\bar{e}=\bar{E}\right.}-x(q,\bar{e})\right]\frac{dw}{d\bar{e}}=-\left|w(\bar{e},\bar{E})x_{\bar{e}}\right|+d', \tag{20}$$

The strategic effect $y_Q\frac{\partial Q}{\partial \bar{e}}_{\left|\frac{dw}{d\bar{e}}=0\right.}$ is unchanged from the unilateral case. However, the price effect $\left[y_Q\frac{\partial Q}{\partial w}-x(q,\bar{e})\right]\frac{dw}{d\bar{e}}$ is moderated. To the extent that $\frac{dw}{d\bar{e}}>0$, the price effect now works in two opposite ways. Instead of providing another strategic effect which makes environmental policy more stringent, the term $y_Q\frac{\partial Q}{\partial w}_{\left|\bar{e}=\bar{E}\right.}\frac{dw}{d\bar{e}}$ now pulls in the same direction as the ordinary strategic effect $y_Q\frac{\partial Q}{\partial \bar{e}}_{\left|\frac{dw}{d\bar{e}}=0\right.}$. This happens because when $\bar{e}=\bar{E}$, we have $\frac{\partial Q}{\partial w}<0$ instead of $\frac{\partial Q}{\partial w}>0$ as in the unilateral case.

We denote the terms $y_Q\left[\frac{\partial Q}{\partial \bar{e}}_{\left|\frac{dw}{d\bar{e}}=0\right.}+\frac{\partial Q}{\partial w}_{\left|\bar{e}=\bar{E}\right.}\frac{dw}{d\bar{e}}\right]$ the "combined strategic effect". On the other hand, the term $-x(q,\bar{e})\frac{dw}{d\bar{e}}$ still provides an incentive to set a stringent environmental policy since a stringent policy still yields a cost reduction.

Assume $\frac{\partial w}{\partial \bar{e}}>0$, the following proposition explores the two policy outcomes:

Proposition 4 *In the policy game with a global pollution abatement market environmental policy will be either stringent or lax according to:*

1. *If* $y_Q\left[\frac{\partial Q}{\partial \bar{e}}_{\left|\frac{dw}{d\bar{e}}=0\right.}+\frac{\partial Q}{\partial w}_{\left|\bar{e}=\bar{E}\right.}\frac{dw}{d\bar{e}}\right]<x(q,\bar{e})\frac{dw}{d\bar{e}}$, *that is "the combined strategic effect" is dominated by the "environmental R&D cost reduction", LS is negative, and HS must be negative. Hence, governments will set a stringent environmental policy.*

2. *If* $y_Q \left[\frac{\partial Q}{\partial \bar{e}} \Big|_{\frac{dw}{d\bar{e}}=0} + \frac{\partial Q}{\partial w} \Big|_{\bar{e}=\bar{E}} \frac{dw}{d\bar{e}} \right] > x(q, \bar{e}) \frac{dw}{d\bar{e}}$, *that is "the combined strategic effect" dominates the "environmental R&D cost reduction",* LS *is positive, and* HS *must be positive. Hence, governments will set a lax environmental policy.*

Note that $\frac{\partial w}{\partial \bar{e}} x_q > |w x_{q\bar{e}}|$ is no longer a sufficient condition for environmental policy to be stringent. We may have $\frac{\partial w}{\partial \bar{e}} x_q > |w x_{q\bar{e}}|$, but all the same $\frac{dq}{d\bar{e}} \big|_{\frac{dw}{d\bar{e}} \neq 0} > 0$. The intuition is that even though the absolute competitiveness of the domestic firm is increasing when the emission quota is tightened, the relative competitiveness is not. As the price on pollution abatement falls, the foreign firm also benefits, and hence, we may have $\frac{dq}{d\bar{e}} \big|_{\frac{dw}{d\bar{e}} \neq 0} > 0$ even if $\frac{\partial w}{\partial \bar{e}} x_q > |w x_{q\bar{e}}|$.

The difference between the unilateral and the global case is examplified in the next section.

6 Example

It is not trivial to find an emission function and an export demand function which make it possible to solve the model analytically. Combined with the linear demand function $p = m - q - Q$, the emission function $f(x, q) = (\frac{v}{\sigma x + \mu}) q$ is especially simple to work with. This implies that emissions are proportional to output, and that pollution abatement services reduce the emission intensity of production. There are diminishing returns to abatement effort, and emissions are normal factors. Finally, we apply $f(n) = \frac{2\beta^2}{3(n+1)^{\phi}}$, $\phi \geq 0$, for the entry costs.

Note also that the emission function inhibits increasing returns to production scale q with respect to the effect of abatement. That is, the cost wx "per abated emissions" $((\frac{v}{\mu} - \frac{v}{\sigma x + \mu}) q)$ for any abatement level x, and for a given price w, is decreasing in the level of output. This is clearly the case if the solution to the pollution problem at hand is to redesign parts of the production process. One example is the process modifications in industrial burners in order to reduce emissions of NO_x (see World Bank, Pollution Abatement Handbook [25]). Hartman, Wheeler and Singh [11] also report that "*average abatement costs drop sharply as abatement volume increases*" in their study of the cement, pulp and paper and iron and steel industries.

The example is solved in the Appendix C1. Here, we illustrate with results from one version of the model: Let $\sigma = v = \mu = 1$, $p = 30 - q - Q$ where p is the export market price, $\alpha = 0.3$, and $\beta = 3$. Solving the model for different ϕ, yields the following schedules for marginal cost $w x_q$ (See Figure 1):

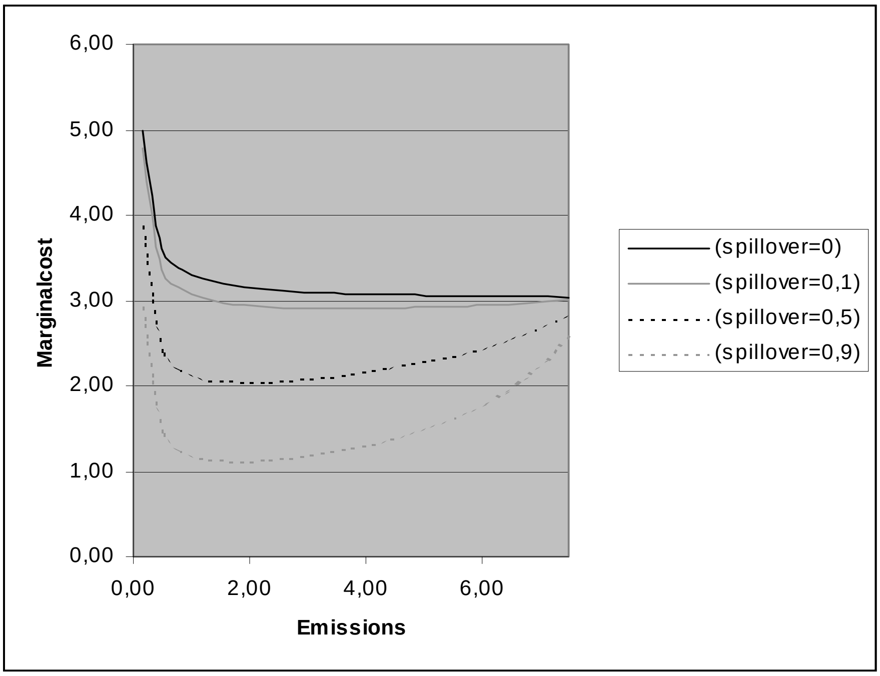

Figure 1. Emissions and competitiveness

Note that with no spillovers i.e. $\phi = 0$, competitiveness is hampered as the emission quota is decreased (moving from right to left along the x-axis). However, even with spillovers as small as $\phi = 0.1$, competitiveness is improving as the emission quota is reduced from 7.5 to 4. With more spillovers, that is, $\phi = 0.5$ or 0.9, the effect is strengthened.

We then turn the maximization of net surpluss in the unilateral policy and policy game case:

Table I

Game type	emiss.red.	*mac.*	*med.*	ϕ	Domestic NS
Unilateral policy	88%	(21.2)	(2.4)	(0.0)	(59.9)
Policy game	(63%)	(7.5)	(7.4)	(0.0)	(66.8)
Unilateral policy	(89%)	(16.5)	(2.2)	(0.5)	(72.6)
Policy game	(72%)	(5.6)	(5.6)	(0.5)	(81.4)

(The emission functions; $s = \frac{q}{x+1}/S = \frac{Q}{X+1}$, export demand; $p = m - q - Q$, fixed cost of entry; $f(n) = \frac{2\beta^2}{3(n+1)^{\phi}}$ and environmental damage; $\delta(\bar{e})^2$. For the parameters we have used: $m = 30$, $\alpha = 0.3$, $\beta = 3$, $\delta = 1$)

There are a number of interesting aspects in these figures. First, domestic emission reductions are much higher in the two unilateral cases than in the policy game cases. The reason is that the price effect is much weaker in the policy game cases (with a common market for pollution abatement services). Second, even though there are no spillovers, $\phi = 0$, marginal abatement cost exceeds marginal environmental damage in the unilateral policy case. The strategic effect $y_Q \frac{\partial Q}{\partial \bar{e}}_{|\frac{dw}{d\bar{e}}=0}$ is negative, but this is by far outweighed by the big value on price effect; $\left| \left[y_Q \frac{\partial Q}{\partial w} - x(q, \bar{e}) \right] \frac{dw}{d\bar{e}} \right|$. (See outcome one in Proposition 3).

Third, observe that environmental policy is neither stringent nor lax in the policy game cases. This is the case, even though a stringent environmental policy improves the absolute competitiveness of the firms when $\phi = 0.5$. Again the reason is the weakened price effect.

Lastly, note that domestic net surplus is higher in the policy game. Profit is shifted towards the domestic firm when the foreign firm is regulated, and this increases net surpluss all other things equal. Note that domestic net surplus is not higher because a greater total demand for abatement solutions leads to lower prices. The level of regulation in both countries are too lax with a global abatement market to induce lower prices on abatement compared with the unilateral case. The price on abatement is 3.90 in the unilateral case (with no spillovers), while the price on abatement in the global abatement market case is 11.40 (with no spillovers).

7 Local markets for environmental R&D

We now assume independent markets for pollution abatement, and differing prices on abatement effort among countries. Let W denote the price on foreign abatement, and the foreign cost function can be written $C(Q, \bar{E}) = WX(Q, \bar{E})$.

The third stage Nash equilibrium output quantities can then be written as; $q = q(w, W, \bar{e}, \bar{E}))$ and $Q = Q(w, W, \bar{e}, \bar{E})$. See Appendix A3 for the derivation of the comparative statics results:

$$\frac{dq}{d\bar{e}}_{|\frac{dw}{d\bar{e}}=0} > 0, \frac{dq}{dw} < 0 \text{ and } \frac{dq}{dW} > 0, \tag{21}$$

$$\frac{dQ}{d\bar{E}}_{|\frac{dw}{d\bar{e}}=0} > 0, \frac{dQ}{dw} > 0 \text{ and } \frac{dQ}{dW} < 0. \tag{22}$$

Domestic demand for pollution abatement services then becomes:

$$x = x(q(w, W, \bar{e}, \bar{E}), \bar{e}).$$

Inverting yields:

$$w = w(\bar{e}, x, \bar{E}, W),$$

and respectively for the foreign upstream market.

The Cournot-Nash, free-entry equilibrium in both upstream markets can be found as above. The price on abatement solutions can finally be written; $w = w(\bar{e}, \bar{E})$ and $W = W(\bar{e}, \bar{E})$. Hence, $q = q(w(\bar{e}, \bar{E}), W(\bar{e}, \bar{E}), \bar{e}, \bar{E})$ and $Q = Q(w(\bar{e}, \bar{E}), W(\bar{e}, \bar{E}), \bar{e}, \bar{E})$ shortened to $q(w, W, \bar{e}, \bar{E})$ and $Q(w, W, \bar{e}, \bar{E})$.

Net surplus NS generated by the domestic and foreign downstream firms, respectively:

$$NS_d = y(q(w, W, \bar{e}, \bar{E}), Q(w, W, \bar{e}, \bar{E}) \tag{23}$$

$$-w(\bar{e}, \bar{E})x(q(w, W, \bar{e}, \bar{E}), \bar{e}) - d(\bar{e}),$$

$$NS_f = Y(q(w, W, \bar{e}, \bar{E}), Q(w, W, \bar{e}, \bar{E})) \tag{24}$$

$$-W(\bar{e}, \bar{E})X(Q(w, W, \bar{e}, \bar{E}), \bar{E}) - d(\bar{E}).$$

where subscript d and f denotes domestic and foreign, respectively. A first order condition for maximizing net surplus then obtains when $\frac{dNS_d}{d\bar{e}} = \frac{dNS_f}{d\bar{E}} = 0$.

As above we only look at one of the first order conditions, and use that $\bar{e} = \bar{E}$ in a symmetric equilibrium. After some rearranging we obtain:

$$y_Q \frac{\partial Q}{\partial \bar{e}}_{\left| \frac{dw}{d\bar{e}} = 0 \right.} + \left[y_Q \frac{\partial Q}{\partial w} - x(q, \bar{e}) \right] \frac{dw}{d\bar{e}} + y_Q \frac{\partial Q}{\partial W} \frac{dW}{d\bar{e}} = - \left| w(\bar{e}, \bar{E}) x_{\bar{e}} \right| + d',$$

Both the strategic effect $y_Q \frac{\partial Q}{\partial \bar{e}}_{\left| \frac{dw}{d\bar{e}} = 0 \right.}$ and the price effect $\left[y_Q \frac{\partial Q}{\partial w} - x(q, \bar{e}) \right] \frac{dw}{d\bar{e}}$ are unchanged from the unilateral policy case. However, there may be a *foreign price effect* $y_Q \frac{\partial Q}{\partial W} \frac{dW}{d\bar{e}}$ which sign is ambiguous. [7]

[7] To the extent that $\frac{dq}{d\bar{e}} > 0$, a stringent domestic environmental policy would *ceteris paribus* lead to an increase in foreign output and foreign demand for abatement effort. This could decrease the foreign price of abatement, i.e. $\frac{dW}{d\bar{e}} > 0$, and further increase the output of the foreign firm through the term $\frac{\partial Q}{\partial W}$. Hence, in this case, the foreign price effect comes as an addition to the normal strategic effect, and we may still get a less stringent policy in the policy game than in the unilateral case. On the other hand, to the extent that $\frac{dq}{d\bar{e}} < 0$, the effect would be the other way around, and the *foreign price effect* would provide an additional incentive to set a stringent policy.

In our numerical example with a linear export demand and a proportional emission function, it turns out that the foreign price effect vanishes when $\phi = 0$ i.e. $\frac{dW}{d\bar{e}} = \frac{dw}{d\bar{E}} = 0$ (this is an artifact of that particular model). Below we compare the results from the two upstream market set-ups:

Table II

Policy game	% emiss.red.	*mac.*	*med.*	Domestic NS
Local markets	(88%)	(24.2)	(2.4)	(78.1)
Global markets	(63%)	(7.5)	(7.4)	(66.8)

($m = 30$, $\alpha = 0.3$, $\beta = 3$, $\phi = 0$ and $\delta = 1$)

Note that net surplus is higher in the policy game with two local markets than with one global market. The reason is that the emission quota is set much more stringent in the policy game with two local markets. This is possible because the price effect $\left[y_Q \frac{\partial Q}{\partial w} - x(q, \bar{e})\right] \frac{dw}{d\bar{e}}$, which favours a stringent policy, is stronger with two local markets due to the difference in sign on the derivative $\frac{\partial Q}{\partial w}$. Actually, in our example, the policy equilibrium with two local markets, is very close to the optimum when joint welfare is maximized. On the other hand, the policy equilibrium in the global market case is a typical Prisoners Dilemma.

8 Abatement subsidies

Since there is more than one externality present in the model, net surpluss is likely to improve if more policy instruments become available. Increasing the number of instruments could also change the conclusions about the desirability of a stringent environmental policy. From the point of view of the domestic government the first best would be 1) to have a regulated monopoly in the upstream sector supplying abatement services at price equal to marginal cost α, 2) to subsidize export directly and 3) to set the level of environmental regulation to equalize marginal abatement cost and marginal environmental damages[8]. The GATT treaty includes measures designed to keep governments from using point 2) above. Further, it may be a problem for governments to

[8]Point 2) and 3) is shown by Barrett[1]. Point 1) should be evident since there are no difference between the R&D firms in the model, and duplicating fixed cost only serves to increase competition between up-stream firms.

regulate a pollution abatement monopoly, that is, choose the right technology and price.Then second best solutions may occur.

One option for the government is to subsidize the abatement costs of the downstream firms. Such a subsidy is explicitly mentioned in the GATT rules as a non-actional subsidy provided that the subsidy is limited to 20% of costs (see point c), Article 8, Part 4, in Agreement on Subsidies and Countervailing Measures, the GATT treaty [7]). Alternatively, the government may choose to subsidize the abatement firms directly by paying a part of their entry costs. This could possibly qualify as assistance for research activities defined as "pre-competitive development activity" (see point a), Article 8, Part 4, in Agreement on Subsidies and Countervailing Measures, the GATT treaty [7]). Such a subsidy is limited to 50% of costs.

Let $\Gamma \leq 0,2$ denote the share of the downstream industry's abatement costs paid by the government. The cost of the downstream firm is then:

$$c(q, \bar{e}) = (1 - \Gamma) w x(q, \bar{e}), \tag{25}$$

which implies that downstream output can be written $q = q((1 - \Gamma)w, \bar{e})$. Note that the subsidy directly improves the competitiveness of the downstream firm.

Further, the subsidy works through the upstream market. The upstream demand function becomes: $x = x(q((1-\Gamma)w, \bar{e}), \bar{e})$ which can be inverted to $w = \frac{w(\bar{e},x)}{(1-\Gamma)}$ where w is the price on abatement effort charged by the upstream firms. Solving as in Section 2 yields $x_i = x_i(n, \bar{e}, \Gamma)$. By inserting back into the profit expression, we get $n = n(\bar{e}, \Gamma)$, and finally $w = w(\bar{e}, \Gamma)$. Note that $\frac{\partial w}{\partial \Gamma} > 0$ is possible, and in fact is the case if we solve for a subsidy in our example. The reason is that the subsidy makes demand for abatement services more inelastic, and thereby allows a higher mark-up on pollution abatement services! However, we may still have $\frac{\partial q}{\partial \Gamma} > 0$, if the direct effect of the subsidy on marginal cost $-wx_q$ dominates the indirect effect $(1-\Gamma)x_q \frac{\partial w}{\partial \Gamma}$, which is the case in our example.

Looking at the net surplus maximum in the unilateral case, the following proposition follows from the first order conditions (see Appendix D):

Proposition 5 *If $\frac{\partial w}{\partial \bar{e}}, \frac{\partial w}{\partial \Gamma} > 0$, and if $\frac{\partial q}{\partial \Gamma} > 0$ and $\frac{\partial q}{\partial \bar{e}} < 0$, environmental policy should always be stringent. If $\frac{\partial w}{\partial \bar{e}}, \frac{\partial w}{\partial \Gamma}, \frac{\partial q}{\partial \Gamma}, \frac{\partial q}{\partial \bar{e}} > 0$, environmental policy should be stringent as long as $\frac{\partial w}{\partial \bar{e}} > \frac{\partial w}{\partial \Gamma} \frac{\frac{dq}{d\bar{e}}}{\frac{dq}{d\Gamma}}$.*

Proof. See Appendix D. ■

If environmental policy spurs competitiveness i.e. $\frac{\partial q}{\partial \bar{e}} < 0$, environmental policy should be set stringent even if an abatement subsidy is used. Further, even if environmental policy does not spur competitiveness i.e. $\frac{\partial q}{\partial \bar{e}} > 0$, the government may still choose to set a stringent environmental policy. Thus, in general, the presence of an abatement subsidy does not remove the incentives for setting a stringent environmental policy. The result is clearly influenced by the fact that the price on pollution abatement services is distorted upwards by the subsidy i.e. $\frac{\partial w}{\partial \Gamma} > 0$. This makes marginal abatement cost appear higher, and consequently, marginal abatement cost should exceed marginal environmental damage.

With respect to an entry subsidy, it is harder to get unambiguous results. We have therefore analyzed both types of subsidies with the help of our numerical model (see Appendix C6 for the analytical treatment of the subsidies). Optimal policies with no spillovers are given:

Table III

Unilateral policy	emiss.red.	*mac.*	*med.*	% subsidy	Domestic NS
No subsidies	88%	(21.2)	(2.4)	(0%)	(59.9)
Abatement subsidy	88%	(24.3)	(2.4)	(20%)	(59.5)
Entry subsidy	84%	(12.2)	(3.2)	(50%)	(54.5)

(The emission functions; $s = \frac{q}{x+1}/S = \frac{Q}{X+1}$, export demand; $p = m - q - Q$, fixed cost of entry; $f(n) = \frac{2\beta^2}{3}$ and environmental damage; $\delta(\bar{e})^2$. For the parameters we have used: $m = 30$, $\alpha = 0.3$, $\beta = 3$, $\delta = 1$)

Some moments are worth mentioning. Maybe the most striking result from the simulation is that the subsidies do not improve net surpluss as long as spillovers are absent. With respect to the abatement subsidy, it allows a higher mark-up, consequently entry increases and we get too many firms which each supplies to few abatement services. The story is much the same with an entry subsidy. The entry subsidy leads to too much entry which is inefficient as long as each firm reduces their output of abatement services. (See for instance Mankiw and Whinston [16] for a general analysis of free entry and social efficiency in Cournot markets).

Secondly, note that a stringent environmental policy is always optimal even though subsidies are provided and environmental policy does not spur competitiveness (the no spillovers case).

9 Discussion

In our model the pollution abatement technology does not improve the higher the number of environmental innovation firms, that is, there are no *love of variety* effects as in other contributions with an upstream-downstream structure. Hence, the only mechanism through which a more stringent environmental policy works, is to enlarge the market for new pollution abatement techniques and allow for lower mark-ups. Note that a mark-up is necessary in order for the engineering firms to cover their fixed costs. The analysis in the paper, at least as long as $\phi = 0$ (the no spillover case), could therefore be interpreted as a sort of bench mark. Introducing a *love of variety* effect would presumably only strengthen the case for a stringent environmental policy, although less fierce price competition between abatement suppliers could pull in the other direction.

Our work also is also related to the empirical literature on experience curves. In its basic form, an experience curve explores the causal relationship between accumulated production at time t and average cost of production at time t [12]. The results derived in Section 3 should hold for all kinds of development processes for which a higher demand leads to a lower price. As long as the stringency of environmental policy and the price on pollution abatement services are negatively correlated, environmental policy will have a price effect. Further, when such price effects do not spill over to foreign and competing countries, policy should be set more stringent than without this effect.

Further, as shown in the paper, matters are different when the price effect spills over to other countries as in the case with a global abatement market. The policy equilibrium is then likely to be a Prisoners Dilemma, and some coordination of either environmental policy or research effort may be warranted. Note that having a global market for abatement solutions is not the only way the price effect could spill over. Another possible implementation could be to have to local markets, but to let knowledge about abatement solutions spill over. Within the current set up this could be accomplished by letting the upstream entry cost be dependent on the total number of firms, that is, the sum of domestic and foreign upstream firms.

Some caveats are in order. For example, the modelling of positive externalities in the abatement service sector has an *ad hoc* flavor. A better approach would be to have sequential entry in the upstream industry, and decreasing entry cost in line with the "*standing on the shoulders of others*" argument (see Romer [20]). On the other hand, this would have required a dynamic model of much higher complexity. Further, we focus on examples with a high upstream entry cost and a low marginal cost of providing abatement solutions. Clearly, if the fixed cost is low, many firms will enter the pollution abatement service sector for any environmental policy, and our case will approach the case for which $\frac{\partial w}{\partial \bar{e}} = 0$.

Finally, the analysis so far does not contain any comparison of different environmental policy instruments. In the Appendix we solve the model for a proportional emission standard. Unfortunately, we are unable to draw any general conclusions about the desirability of different instruments. In general, it is more difficult to solve the model for an emission tax. Hence, future research aiming to compare different instruments, will have to rely more heavily on numerical simulations than analytical approaches.

The paper provides both some support for, and a possible explanation of the Porter-hypothesis. One could argue that the model is quite special; we only look at Cournot competition, many firms demand the same pollution abatement techniques, but competes on different markeds etc. However, the result that policy should be more stringent when a well developed market for abatement services does not exist, and are likely to be imperfectly competitive, clearly has some general appeal. Further, as importantly, we have discovered that even though a weak form of the Porter-hypothesis could hold, governments may still set a weak environmental policy in the Nash policy equilibrium provided that the market for abatement services is a global market.

References

[1] S. Barrett, Strategic environmental policy and international trade, *J. Public Econom.* **54**, p. 325-338 (1994).

[2] R. L. Bradford and R. D. Simpson, Taxing Variable Cost: Environmental Regulation as Industrial Policy, *J. Environ. Econom. Management* **30**, p. 282-300 (1996).

[3] J. Brander and B. Spencer, Export Subsidies and International Market Share Rivalry, *J. Internat. Econom.* **18**, p. 83-100 (1985).

[4] D. Burtraw and K. Palmer, The Papparazzi Take a Look at a Living Legend: The SO_2 Cap and Trade Program for Coal Fired Power Plants in the U.S., presented at the work-shop *Competing Approaches to Environmental Regulation*, Resources for the Future, Dec. 2002, www.rff.org/effectiveness and efficiency/

[5] K. Conrad, Taxes and Subsidies for Pollution-Intensive Industries as Trade Policy, *J. of Environ. Econom. Management* **25**, p. 121-135 (1993).

[6] P. B. Downing and L. J. White, Innovation in Pollution Control, *J. of Environ. Econom. Management* **13**, p. 18-29 (1986).

[7] Agreement on Subsidies and Countervailing Measures, the GATT Uruguay Round, in St. prp. nr. 65, The Ministry of Foreign Affairs, Norway (1994).

[8] H. Gravelle and R. Rees, Micro economics, Longman Group UK Limited, (1992).

[9] M. Greaker, "Strategic Environmental Policy: Eco dumping or a Green Strategy?", *J. of Environ. Econom. Management* **45**, p.692-707 (2003).

[10] J. I. Haaland and I. Wooton, International Competition for Multinational Investment, *Scand. J. of Econom.* **101**, p. 631-649 (1999).

[11] R. S. Hartman, D. Wheeler and M. Singh, The cost of air pollution abatement, *Applied Economics* 29 (1997), p. 759-774.

[12] International Energy Agency, Experience Curves for Energy Technology Policy, OECD/IEA, Paris, France (2000).

[13] A. B. Jaffe, S.R. Peterson, P.R. Portney and R.N. Stavins, Environmental Regulation and the Competitiveness of U.S. Manufacturing: What Does the Evidence Tell Us?. *J. of Economic Literature*, Vol. XXXIII, pp. 132-163 (1995).

[14] C. Jung, K. Krutilla and R. Boyd, Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives, *J. of Environ. Econom. Management* **30**, p. 95-111 (1996).

[15] P. W. Kennedy, Equilibrium Pollution Taxes in Open Economies with Imperfect Competition, *J. of Environ. Econom. Management* **27**, p. 49-63 (1994).

[16] N. G. Mankiw and M. D. Whinston, Free entry and social efficiency, *Rand J. of Economics* 17, p. 48-58, (1986).

[17] M. E. Porter, America's Green Strategy, *Scientific American*, Apr., p. 168, (1991).

[18] M. E. Porter and C. von der Linde, Green and Competitive, *Harvard Business Rev.*, September-October (1995).

[19] M. Rauscher, On Ecological Dumping, Oxford Economic Papers, 46, p. 822-840 (1994).

[20] P. M. Romer, Endogenous Technological Change, *Journal of Political Economy*, Oct. 1990, 98 (5).

[21] J. Tirole, The Theory of Industrial Organization, The MIT Press (1997).

[22] A. Ulph, Environmental Policy and International Trade when Governments and Producers Act Strategically, *J. of Environ. Econom. Management* **30**, p. 265-281 (1996).

[23] A. Ulph and D. Ulph, Trade, Strategic Innovation and Strategic Environmental Policy: A General Analysis, Nota Di Lavoro, Fon-

dazione Eni Enrico Mattei, Milano (1995).
[24] D. Ulph, Strategic Innovation and Strategic Environmental Policy, in *Trade, Innovation, Environment* (ed. Carlo Carraro), Kluwer Academic Publishers (1994).
[25] World Bank, Pollution Prevention and Abatement Handbook, The World Bank Group, Washington D.C. (1998).

A Derivation of the export market Nash equilibrium

A.1 Unilateral policy (proof of Prop. 2)

Total revenues of the domestic and the foreign firms are $y(q,Q)$ and $Y(q,Q)$ respectively. Assuming that the two products are substitutes, we have y_Q, $Y_q < 0$. It is also assumed that y_{qQ} and Y_{Qq} are negative in order to ensure that the outputs of the two firms are strategic substitutes.

Given the emission standard $\bar{e}$ and the supply of environmental R&D x, both firms are taken to maximize profits:

$$\max_q \pi = y(q,Q) \text{ given } f(x,q) \leq \bar{e} \tag{26}$$

and

$$\max_Q \Pi = Y(q,Q) \tag{27}$$

respectively. Note that the foreign representative firm has no constraint, because there is no foreign environmental policy.

The condition $f(x,q) \leq \bar{e}$ can be rewritten $q \leq q(x,\bar{e})$. Thus, the emission quota actually puts an upper bound on output since the supply of environmental R&D is given from the stage before the market game. One question is then whether the firm will choose excess environmental R&D so that $f(x,q) < \bar{e}$ in the third stage Nash equilibrium. If the firm has invested in excess environmental R&D, the firm must be on its unbounded reaction curve given by:

$$\frac{\partial}{\partial q}[y(q,Q)] = y_q = 0. \tag{28}$$

Since additional environmental R&D has no effect upon the reaction curve, and thereby, not on the Nash-equilibrium output, surplus environmental R&D can only increase costs. Hence, we are left with the alternative that the firm invests exactly up to the level where the emission quota starts to bite i.e. $f(x,q) = \bar{e}$.

In the case of a binding emission quota, the three stage game with sequential R&D and output decisions is in fact identical to a two stage game with simultaneous R&D and output decisions.[9] We can therefore proceed directly to look at second stage profit maximization:

$$\max_x \pi = y(q(x,\bar{e}),Q) - wx$$

Since $q = q(x,\bar{e})$ and $x = x(q,\bar{e})$, this can alternatively be expressed:

$$\max_q \pi = y(q,Q) - wx(q,\bar{e}) \tag{29}$$

The two first order conditions for profit maximization are then:

$$\partial\pi/\partial q = y_q - wx_q = 0, \tag{30}$$

and

$$\partial\Pi/\partial Q = Y_Q = 0. \tag{31}$$

The two first-order conditions determine the Nash-equilibrium output quantities given the domestic emission quota. It is assumed that the second-order conditions for profit maximization hold, and that the uniqueness condition for the Nash-equilibrium is met[10]. Output quantities can then be written as functions of the emission quota, and the price of pollution abatement in the following manner; $q = q(w,\bar{e})$ and $Q = Q(w,\bar{e})$.

Further, we look at the comparative statics of the Nash equilibrium in the export market taking into consideration that $\frac{\partial w}{\partial \bar{e}} \neq 0$. Total differentiation of the system (30) and (31) yields:

$$\begin{aligned}(y_{qq} - wx_{qq})dq + y_{qQ}dQ - (wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q)d\bar{e} - x_q dw &= 0,\\ Y_{Qq}dq + Y_{QQ}dQ &= 0.\end{aligned}$$

Setting $dw = 0$, and using that $dQ = -Y_{Qq}dq/Y_{QQ}$ we obtain:

$$\frac{dq}{d\bar{e}} = \frac{(wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q)Y_{QQ}}{[(y_{qq} - wx_{qq})Y_{QQ} - y_{qQ}Y_{Qq}]}$$

Further, using that $dq = -Y_{QQ}dQ/Y_{Qq}$, we also obtain:

$$\frac{dQ}{d\bar{e}} = \frac{-(wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q)Y_{Qq}}{[(y_{qq} - wx_{qq})Y_{QQ} - y_{qQ}Y_{Qq}]}$$

The denominator in both expressions is positive because of the assumption of Nash-equilibrium uniqueness. Y_{QQ} is negative because of

[9] Consequently, there is also no difference between the closed loop and the open loop solution concepts.

[10] See the discussion about uniqueness in Tirole[21], page 225-226.

the assumption that the second order conditions for profit maximum hold, and Y_{Qq} is negative because of the assumption about outputs being strategic substitutes. Lastly, $x_{q\bar{e}} < 0$ because of the assumption that emissions are normal inputs. Hence, we have $\frac{dq}{d\bar{e}}|_{\frac{\partial w}{\partial \bar{e}}=0} > 0$ and $\frac{dQ}{d\bar{e}}|_{\frac{\partial w}{\partial \bar{e}}=0} < 0$.However, we also note that if $\frac{\partial w}{\partial \bar{e}}x_q > |wx_{q\bar{e}}|$, we have $\frac{dq}{d\bar{e}} < 0$, that is, competitiveness is improving in the emission quota (proof of proposition 2).

By following the same approach, that is setting $d\bar{e} = 0$ etc., it is also easy to show that:

$$\frac{dq}{dw} = \frac{x_q Y_{QQ}}{[(y_{qq} - wx_{qq})Y_{QQ} - y_{qQ}Y_{Qq}]}$$

Further, we also obtain:

$$\frac{dQ}{d\bar{e}} = \frac{-x_q Y_{Qq}}{[(y_{qq} - wx_{qq})Y_{QQ} - y_{qQ}Y_{Qq}]}$$

and hence, $\frac{dq}{dw} < 0$ and $\frac{dQ}{dw} > 0$.

A.2 Global market for pollution abatement

As shown above, the third and second stage of the game can be treated as a one stage game in quantities. The two first order conditions for profit maximization are now:

$$\partial\pi/\partial q = y_q - wx_q = 0, \tag{32}$$

and

$$\partial\Pi/\partial Q = Y_Q - wX_Q = 0. \tag{33}$$

The two first-order conditions determine the Nash-equilibrium output quantities given the emission quotas. Total differentiation of the system (32) and (33) yields:

$$(y_{qq} - wx_{qq})dq + y_{qQ}dQ - (wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q)d\bar{e} - \frac{\partial w}{\partial \bar{E}}x_q d\bar{E} - x_q dw = 0,$$

$$Y_{Qq}dq + (Y_{QQ} - wX_{QQ})dQ - \frac{\partial w}{\partial \bar{e}}X_Q d\bar{e} - (wX_{Q\bar{E}} + \frac{\partial w}{\partial \bar{E}}X_Q)d\bar{E} - X_Q dw = 0.$$

Setting $d\bar{e} = d\bar{E} = 0$, we obtain:

$$\frac{dq}{dw} = \frac{[(Y_{QQ} - wX_{QQ})x_q - y_{qQ}X_Q]}{[(y_{qq} - wx_{qq})(Y_{QQ} - wX_{QQ}) - y_{qQ}Y_{Qq}]}.$$

$$\frac{dQ}{dw} = \frac{[X_Q(y_{qq} - wx_{qq}) - x_q Y_{Qq}]}{[(Y_{QQ} - wX_{QQ})(y_{qq} - wx_{qq}) - y_{qQ}Y_{Qq}]}.$$

The uniqueness assumption ensures that the denominator in both expressions is positive. Further, in a symmetric, unique equilibrium for which $\bar{e} = \bar{E}$, we must have $x_q = X_Q$, and $|Y_{QQ} - wX_{QQ}| > |y_{qQ}|$. Hence, we have $\frac{dq}{dw}\big|_{\bar{e}=\bar{E}} < 0$ and $\frac{dQ}{dw}\big|_{\bar{e}=\bar{E}} < 0$.

Further, setting $dw = d\bar{E} = 0$, we obtain:

$$\frac{dq}{d\bar{e}} = \frac{(Y_{QQ} - wX_{QQ})(wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q) - y_{qQ}X_Q\frac{\partial w}{\partial \bar{e}}}{[(Y_{QQ} - wX_{QQ})(y_{qq} - wx_{qq}) - y_{qQ}Y_{Qq}]}.$$

$$\frac{dQ}{d\bar{e}} = \frac{-Y_{Qq}(wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q) + (y_{qq} - wx_{qq})X_Q\frac{\partial w}{\partial \bar{e}}}{[(Y_{QQ} - wX_{QQ})(y_{qq} - wx_{qq}) - y_{qQ}Y_{Qq}]}$$

Firstly, note that $\frac{dq}{d\bar{e}}\big|_{\frac{\partial w}{\partial \bar{e}}=0} > 0$. Further, note that $\frac{\partial w}{\partial \bar{e}}x_q > |wx_{q\bar{e}}|$, is no longer a sufficient condition for having either $\frac{dq}{d\bar{e}} < 0$ or $\frac{dQ}{d\bar{e}} > 0$.

By following the same approach, that is setting $dw, d\bar{e} = 0$, it is also easy to show that $\frac{dQ}{d\bar{E}}\big|_{\frac{\partial w}{\partial \bar{e}}=0} > 0$.

A.3 Local markets for pollution abatement

The two first order conditions for profit maximization are now:

$$\partial\pi/\partial q = y_q - wx_q = 0, \tag{34}$$

and

$$\partial\Pi/\partial Q = Y_Q - WX_Q = 0. \tag{35}$$

The two first-order conditions determine the Nash-equilibrium output quantities given the emission quotas. Total differentiation of the system (34) and (35) yields:

$$(y_{qq} - wx_{qq})dq + y_{qQ}dQ - (wx_{q\bar{e}} + \frac{\partial w}{\partial \bar{e}}x_q)d\bar{e} - \frac{\partial w}{\partial \bar{E}}x_q d\bar{E} - x_q dw = 0,$$

$$Y_{Qq}dq + (Y_{QQ} - WX_{QQ})dQ - \frac{\partial w}{\partial \bar{e}}X_Q d\bar{e} - (WX_{Q\bar{E}} + \frac{\partial W}{\partial \bar{E}}X_Q)d\bar{E} - X_Q dW = 0.$$

Setting $d\bar{e} = d\bar{E} = dW = 0$, we obtain:

$$\frac{dq}{dw} = \frac{x_q(Y_{QQ} - WX_{QQ})}{[(y_{qq} - wx_{qq})(Y_{QQ} - wX_{QQ}) - y_{qQ}Y_{Qq}]},$$

which is negative. And,

$$\frac{dQ}{dw} = \frac{-x_q Y_{Qq}}{[(y_{qq} - wx_{qq})(Y_{QQ} - wX_{QQ}) - y_{qQ}Y_{Qq}]}.$$

which is positive. By following the same approach, that is setting $dw, d\bar{e}, d\bar{E} = 0$, it is also easy to show that $\frac{dq}{dW} > 0$ and $\frac{dQ}{dW} < 0$ etc.

B The upstream market for abatement solutions

The demand function for pollution abatement services is:

$$w = w(\bar{e}, x).$$

Differentiating we get:

$$\frac{dw}{dx} = \frac{1}{x_q \frac{dq}{dw}} < 0,$$

which makes the demand curve downward sloping, and further:

$$\frac{dw}{d\bar{e}} = \frac{x_q \frac{\partial q}{\partial \bar{e}} + x_{\bar{e}}}{-x_q \frac{\partial q}{\partial w}}.$$

The sign on the nominator is ambiguous. The direct effect of a higher emission quota i.e. $\bar{e} \uparrow$, is to decrease the demand for pollution abatement (the last term in the nominator). However, setting a higher emission quota also leads to higher downstream output in Nash-equilibrium, see (5) above. This boosts the demand for pollution abatement. We assume that the direct effect dominates, and hence, by assumption: $\frac{\partial w}{\partial \bar{e}} < 0$.

Each abatement supply firm maximizes profit Ω taking n as given:

$$\max_{x_i} \left[w(\bar{e}, \sum_{i=1}^{n} x_i) - \alpha \right] x_i - f(n),$$

from which we obtain the following first-order condition (assuming symmetric firms):

$$\frac{\partial w}{\partial x}\bar{x} + w(\bar{e}, n\bar{x}) - \alpha = 0.$$

Further, assuming that the second order condition is fulfilled i.e. $\partial^2\Omega/\partial(x_i)^2 < 0$, and solving this problem, we get: $x_1 = ... = x_i = ... = x_n = \bar{x}(n, \bar{e})$. By differentiating the first order condition, we can look at the derivatives of $\bar{x}(n, \bar{e})$:

$$\frac{d\bar{x}(n, \bar{e})}{dn_{|d\bar{e}=0}} = -\frac{\left[\frac{\partial^2 w}{\partial n \partial x} + \frac{\partial w}{\partial x}\right]\bar{x}}{\partial^2\Omega/\partial(x_i)^2} < 0. \tag{36}$$

$$\frac{d\bar{x}(n, \bar{e})}{d\bar{e}_{|dn=0}} = -\frac{\frac{\partial^2 w}{\partial \bar{e} \partial x}\bar{x} + \frac{\partial w}{\partial \bar{e}}}{\partial^2\Omega/\partial(x_i)^2}. \tag{37}$$

The nominator in (37) is hard to sign, since we do not know the sign on the cross-derivative. If $\frac{\partial^2 w}{\partial \bar{e} \partial x} < 0$, we get $\frac{d\bar{x}(n,\bar{e})}{d\bar{e}_{|dn=0}} < 0$.

Knowing $\bar{x}(n, \bar{e})$, we may find n from the zero profit condition:

$$\Omega_i = [w(\bar{e}, n\bar{x}(n, \bar{e})) - \alpha]\, \bar{x}(n, \bar{e}) - f(n) = 0,$$

which yields: $n = n(\bar{e})$. We differentiate the zero profit condition, and get:

$$\frac{dn}{d\bar{e}} = -\frac{\left[\frac{\partial w}{\partial \bar{e}} + n\frac{\partial w}{\partial x}\frac{d\bar{x}}{d\bar{e}}\right]\bar{x} + [w(\bar{e}, n\bar{x}) - \alpha]\,\frac{d\bar{x}}{d\bar{e}}}{\frac{\partial w}{\partial x}\left[\bar{x}(n, \bar{e}) + n\frac{d\bar{x}}{dn}\right]\bar{x} + [w(\bar{e}, n\bar{x}) - \alpha]\,\frac{d\bar{x}}{dn} + f'}$$

By expanding $w(\bar{e}, n(\bar{e})\bar{x}(n(\bar{e}), \bar{e}))$ we get the following:

$$\frac{dw}{d\bar{e}} = \frac{\partial w}{\partial \bar{e}} + \frac{\partial w}{\partial x}\left[n\frac{d\bar{x}}{d\bar{e}} + \bar{x}\frac{dn}{d\bar{e}} + n\frac{d\bar{x}}{dn}\frac{dn}{d\bar{e}}\right].$$

From (9) we have $\frac{\partial w}{\partial x} < 0$, and we have assumed $\frac{\partial w}{\partial \bar{e}} < 0$. Hence, in order to have $\frac{dw}{d\bar{e}} > 0$, the terms in brackets, have to be negative. The first term is negative if $\frac{\partial^2 w}{\partial \bar{e} \partial x} < 0$, while the latter terms take different signs respectively of $\frac{dn}{d\bar{e}}$ being negative or positive.

Assume that $\frac{d\bar{x}}{d\bar{e}} < 0$, $\frac{\partial w}{\partial \bar{e}} + n\frac{\partial w}{\partial x}\frac{d\bar{x}}{d\bar{e}} > 0$ and that $\bar{x} + n\frac{d\bar{x}}{dn} = 0$. We then have $\frac{dw}{d\bar{e}} > 0$, but we still cannot sign $\frac{dn}{d\bar{e}}$.

C Solving the examples

C.1 Unilateral policy

Let emissions s be given by $f(x, q) = (\frac{\upsilon}{\sigma x + \mu})q$. Given an emission quota $\bar{e}$, the demand for abatement solutions is given: $x = \frac{\upsilon q}{\sigma \bar{e}} - \frac{\mu}{\sigma}$. Further, let export demand be given: $p = m - q - Q$ where p is the export market price and m the market size. We then have for the Nash equilibrium quantities of the domestic and foreign industry:

$$q = \frac{m - 2(\frac{w\upsilon}{\sigma \bar{e}})}{3},$$

$$Q = \frac{m + (\frac{w\upsilon}{\sigma \bar{e}})}{3}.$$

The inverse demand for abatement effort:

$$w = \frac{\upsilon \sigma m \bar{e} - 3\sigma\mu(\bar{e})^2}{2\upsilon^2} - \frac{3(\sigma \bar{e})^2}{2\upsilon^2}x.$$

Define then:

$$\lambda \equiv \frac{\upsilon\sigma m\bar{e} - 3\sigma\mu(\bar{e})^2}{2\upsilon^2},$$

$$\tau \equiv \frac{3(\sigma\bar{e})^2}{2\upsilon^2}.$$

Given n, each R&D firm maximizes:

$$\max_{x_i} \left[\lambda - \tau \sum_{i=1}^{n} x_i - \alpha\right] x_i.$$

Solving the maximization problem yields:

$$x_1 = ... = x_i = ... = x_n = \frac{\lambda - \alpha}{\tau(n+1)}.$$

If f is independent of n, the number of firms in the intermediate goods industry is then decided by the zero profit condition:

$$\frac{1}{\tau}\left[\frac{\lambda - \alpha}{(n+1)}\right]^2 - f = 0$$

from which we obtain:

$$n = \frac{\lambda - \alpha}{\sqrt{\tau f}} - 1.$$

This can then be inserted back into the expression for x_i and w. We have: $x_i = \sqrt{\frac{f}{\tau}}$ and $w = \alpha + \sqrt{\tau f}$. Define $f \equiv \frac{2\beta^2}{3}$. We then get:

$$w = \alpha + \frac{\sigma\bar{e}}{\upsilon}\beta.$$

Hence, we note that we have $\frac{dw}{d\bar{e}} > 0$.

If we include spillovers; $f = \frac{2\beta^2}{3(n+1)^\phi}$, we get for n:

$$n = \left[\frac{\lambda - \alpha}{\sqrt{\tau f}}\right]^{\frac{2}{2-\phi}} - 1,$$

which also makes it possible to solve for the price. In our simulations we have used $\sigma = \upsilon = \mu = 1$.

C.2 A global abatement market

Let $s = \frac{q}{x+1} / S = \frac{Q}{X+1}$. Given an emission quota $\bar{e}/\bar{E}$, the demand for abatement solutions is given: $x = \frac{q}{\bar{e}} - 1/X = \frac{Q}{\bar{E}} - 1$. Further, let export demand be given: $p = m - q - Q$ where p is the export market price and m the market size. The Nash equilibrium quantities of the domestic and foreign industry are then given:

$$q = \frac{m - 2(\frac{w}{\bar{e}}) + (\frac{w}{\bar{E}})}{3},$$

$$Q = \frac{m - 2(\frac{w}{\bar{E}}) + (\frac{w}{\bar{e}})}{3}.$$

Further, total demand Z for abatement effort is:

$$Z = x + X = \frac{m\bar{e}\bar{E}\left[\bar{e} + \bar{E}\right] - 6\bar{e}^2\bar{E}^2 - 2\left[\bar{E}^2 - \bar{e}\bar{E} + \bar{e}^2\right]w}{3\bar{e}^2\bar{E}^2},$$

which can be inverted:

$$w = \frac{1}{2\left[\bar{E}^2 - \bar{e}\bar{E} + \bar{e}^2\right]}\left\{m\bar{e}\bar{E}\left[\bar{e} + \bar{E}\right] - 6\bar{e}^2\bar{E}^2 - 3\bar{e}^2\bar{E}^2 Z\right\}.$$

As above, define:

$$\lambda \equiv \frac{m\bar{e}\bar{E}\left[\bar{e} + \bar{E}\right] - 6\bar{e}^2\bar{E}^2}{2\left[\bar{E}^2 - \bar{e}\bar{E} + \bar{e}^2\right]},$$

$$\tau \equiv \frac{3\bar{e}^2\bar{E}^2}{2\left[\bar{E}^2 - \bar{e}\bar{E} + \bar{e}^2\right]}.$$

We have $Z = \sum_{i=1}^{n} x_i$. Given n, each R&D firm maximizes:

$$\max_{x_i}\left[\lambda - \tau\sum_{i=1}^{n} x_i - \alpha\right]x_i,$$

Which for f independent of n, can be solved as above. We $w = \alpha + \sqrt{\tau f}$. Define $f \equiv \frac{2\beta^2}{3}$. We then get:

$$w = \alpha + \frac{\bar{e}\bar{E}}{\sqrt{\left[\bar{E}^2 + \bar{e}^2 - \bar{e}\bar{E}\right]}}\beta \ (w_{|\bar{e}=\bar{E}} = \alpha + \beta\bar{e}).$$

It is then easy to find the symmetric policy equilibrium by simulating the model in Exel. With $f(n) = \frac{2\beta^2}{3(n+1)^\phi}$, we get for n:

$$n = \left[\frac{\lambda - \alpha}{\sqrt{\frac{2\tau\beta^2}{3}}}\right]^{\frac{2}{2-\phi}} - 1,$$

which also makes it possible to find the policy equilibrium in case of spillovers.

C.3 Two local abatement markets

Using the same model as above, we find that the Nash equilibrium quantities of the domestic and foreign industry can be written:

$$q = \frac{m - 2(\frac{w}{\bar{e}}) + (\frac{W}{\bar{E}})}{3},$$

$$Q = \frac{m - 2(\frac{W}{\bar{E}}) + (\frac{w}{\bar{e}})}{3},$$

where W is the price on abatement in the foreign country. Since the game is symmetric, we only have to look at one of the countries. Domestic demand x for R&D effort is then:

$$x = \frac{m\bar{e}\bar{E} - 3\bar{e}^2\bar{E} + W\bar{e} - 2w\bar{E}}{3\bar{e}^2\bar{E}},$$

which can be inverted:

$$w = \frac{m\bar{e}\bar{E} - 3\bar{e}^2\bar{E} + W\bar{e}}{2\bar{E}} - \frac{3\bar{e}^2}{2}x.$$

Define then:

$$\lambda \equiv \frac{m\bar{e}\bar{E} - 3\bar{e}^2\bar{E} + W\bar{e}}{2\bar{E}},$$

$$\tau \equiv \frac{3\bar{e}^2}{2}.$$

We have $x = \sum_{i=1}^{n} x_i$. Each domestic abatement firm maximizes profit taking n, $\bar{e}$ and W as given, while each foreign abatement firm maximizes profit taking N, $\bar{E}$ and w as given. From above we then know: $n = \frac{\lambda-\alpha}{\sqrt{\tau f}} - 1$, $x_i = \sqrt{\frac{f}{\tau}}$ and $w = \alpha + \sqrt{\tau f}$. Define $f \equiv \frac{2\beta^2}{3}$. We then have:

$$w = \alpha + \beta\bar{e}.$$

And correspondingly:

$$W = \alpha + \beta \bar{E}$$

Hence, in the example, there is no foreign price effect. Once again, it is easy to find the symmetric policy equilibrium. Note that for $\bar{e} = \bar{E}$, the expression for the price is the same in all three cases. It is the different sign on the strategic effect $\frac{\partial Q}{\partial w} \frac{dw}{d\bar{e}}$ which causes the policy equilibria to be different.

C.4 Proportional emission standard

In order to look further into the robustness of $\frac{dw}{d\bar{e}} > 0$, we also look at another example. The emission function for the down stream industry is:

$$f(q, x) = q - \sqrt{qx}, \; x \leq \sqrt{q},$$

where x is abatement effort. Note that this emission function also inhibits increasing returns to production scale q with respect to the effect of abatement. The government sets a proportional emission standard $(1 - r)$, which implies $\frac{e}{q} \leq (1 - r)$. We then have that the demand for abatement solutions can be written:

$$x = r^2 q,$$

and we get the following reduced form cost function:

$$c(q, r) = wr^2 q.$$

let export demand be given: $p = m - q - Q$ where p is the export market price and m the market size. We then have that the Nash equilibrium quantity of the domestic and foreign industry can be written:

$$q = \frac{m - 2wr^2}{3},$$

Further, the inverse demand for R&D effort:

$$w = \frac{mr^2 - 3x}{2r^4},$$

Going through the same exercise as above, we have for the no spillover case:

$$w_{|\phi=0} = \alpha + \frac{\beta}{2r^2}.$$

Hence, the price on pollution abatement is falling in the level of environmental regulation r.

C.5 Abatement subsidy

In the abatement subsidy case, we have for the Nash equilibrium quantities of the domestic and foreign industry:

$$q = \frac{m - 2(\frac{(1-\Gamma)w}{\bar{e}})}{3},$$

$$Q = \frac{m + (\frac{(1-\Gamma)w}{\bar{e}})}{3}.$$

The inverse demand for abatement effort:

$$w = \frac{m\bar{e} - 3(\bar{e})^2}{2(1-\Gamma)} - \frac{3(\bar{e})^2}{2(1-\Gamma)}x.$$

Define then:

$$\lambda \equiv \frac{m\bar{e} - 3(\bar{e})^2}{2(1-\Gamma)},$$

$$\tau \equiv \frac{3(\bar{e})^2}{2(1-\Gamma)}.$$

Going through the same exercise as above, we have: $n = \left[\frac{\lambda-\alpha}{\sqrt{\tau f}}\right]^{\frac{2}{2-\phi}} - 1$, $x_i = \sqrt{\frac{f}{\tau}}$ and $w = \alpha + \sqrt{\tau f}$. Define $f \equiv \frac{2\beta^2}{3}$. We then get:

$$x_i = \frac{2\sqrt{(1-\Gamma)}\beta}{3\bar{e}} \text{ (no spillovers)}$$

$$w = \alpha + \frac{\bar{e}\beta}{\sqrt{1-\Gamma}} \text{ (no spillovers)}$$

$$n = \left[\frac{m\bar{e} - 3(\bar{e})^2 - 2(1-\Gamma)\alpha}{2\sqrt{1-\Gamma}\bar{e}\beta}\right]^{\frac{2}{2-\phi}} - 1 \text{ (general case - with/without spillovers)}$$

Note that we have $\frac{dw}{d\Gamma} > 0$ and $\frac{\partial x_i}{\partial \Gamma} < 0$ in the no spillovers case. However, it is easy to show that marginal cost, that is, $\frac{w(\bar{e},\Gamma)(1-\Gamma)}{\bar{e}} = \frac{\alpha(1-\Gamma)}{\bar{e}} + \sqrt{1-\Gamma}\beta$, is decreasing in Γ, and hence, domestic output is increasing in Γ.

When calculating welfare total subsidy costs, $\Gamma w n \bar{x}$ must be subtracted from net surplus.

C.6 Entry subsidy

An upstream entry subsidy is even simpler to build into our example. With an entry subsidy we have $f(n) = (1-\rho)\frac{2\beta^2}{3(n+1)^\phi}$ where ρ is the share of the entry costs financed by the government. Solving for n we get:

$$n = \left[\frac{m\bar{e} - 3(\bar{e})^2 - 2\alpha}{2\sqrt{1-\rho}\bar{e}\beta}\right]^{\frac{2}{2-\phi}} - 1 \text{ (general case - with/without spillovers).}$$

When calculating welfare total subsidy costs, $\rho n \frac{2\beta^2}{3(n+1)^\phi}$ must be subtracted from net surplus.

D Abatement subsidy - general case

Let Γ denote the share of the downstream industry's abatement costs paid by the government. We then have for the cost of the downstream firm:

$$c(q, \bar{e}) = (1-\Gamma)wx(q, \bar{e}),$$

which implies that downstream output can be written $q = q((1-\Gamma)w, \bar{e})$.

The upstream demand function becomes: $x = x(q((1-\Gamma)w, \bar{e}), \bar{e})$ which can be inverted to yield $w = \frac{w(\bar{e},x)}{(1-\Gamma)}$ where w is the price on abatement effort charged by the upstream firms. Each abatement firm maximizes:

$$\max_{x_i} \left[\frac{w(\bar{e}, \sum_{i=1}^{n} x_i)}{(1-\Gamma)} - \alpha\right] x_i - f(n),$$

from which we obtain the following first-order condition (assuming symmetric firms):

$$\frac{\partial w}{\partial x}\bar{x} + w(\bar{e}, n\bar{x}) - (1-\Gamma)\alpha = 0.$$

Thus, the downstream abatement subsidy has an indirect effect on the upstream market; it lowers the marginal cost of upstream firms. Solving as in Section 2 yields, $x_i = x_i(n, \bar{e}, \Gamma)$. By inserting back into the profit expression, we get $n = n(\bar{e}, \Gamma)$, and finally $w = w(\bar{e}, \Gamma)$. The sign on $\frac{\partial w}{\partial \Gamma}$ is ambiguous, and hence, the signs on $\frac{\partial q}{\partial \Gamma}$ and $\frac{\partial Q}{\partial \Gamma}$ are also ambiguous even though the direct effect of the subsidy is to reduce the price on abatement.

Net surplus, NS, generated by the domestic downstream firm in the deployment subsidy case is given:

$$NS = y(q((1-\Gamma)w(\bar{e}, \Gamma), \bar{e}), Q((1-\Gamma)w(\bar{e}, \Gamma), \bar{e}))$$

$$-(1-\Gamma)w(\bar{e},\Gamma)x(q((1-\Gamma)w(\bar{e},\Gamma),\bar{e}),\bar{e})$$
$$-\Gamma w(\bar{e},\Gamma)x(q((1-\Gamma)w(\bar{e},\Gamma),\bar{e}),\bar{e})-d(\bar{e}),$$

where the two first terms denote downstream firm profit, and the two latter terms are the subsidy costs and the environmental damage costs, respectively. The optimal emission quota and subsidy are given from a set of two first order conditions.

We have for the optimal emission quota:

$$y_Q\frac{dQ}{d\bar{e}}-\Gamma w(\bar{e},\Gamma)x_q\frac{dq}{d\bar{e}}-x\frac{\partial w}{\partial \bar{e}}=w(\bar{e},\Gamma)x_{\bar{e}}+d'. \tag{38}$$

We have for the optimal subsidy:

$$y_Q\frac{dQ}{d\Gamma}-\Gamma w(\bar{e},\Gamma)x_q\frac{dq}{d\Gamma}-x\frac{\partial w}{\partial \Gamma}=0. \tag{39}$$

Rearranging and combining:

$$\frac{y_Q}{\frac{dq}{d\Gamma}}\left[\frac{dQ}{d\bar{e}}\frac{dq}{d\Gamma}-\frac{dQ}{d\Gamma}\frac{dq}{d\bar{e}}\right]+x\left[\frac{\partial w}{\partial \Gamma}\frac{\frac{dq}{d\bar{e}}}{\frac{dq}{d\Gamma}}-\frac{\partial w}{\partial \bar{e}}\right]=w(\bar{e},\Gamma)x_{\bar{e}}+d'. \tag{40}$$

Denote marginal cost of the firm mc_d. We then have $\frac{dQ}{d\bar{e}}\frac{dq}{d\Gamma}=\frac{dQ}{dmc_d}\frac{dmc_d}{d\bar{e}}\frac{dq}{dmc_d}\frac{dmc_d}{d\Gamma}$, and likewise $\frac{dQ}{d\Gamma}\frac{dq}{d\bar{e}}=\frac{dQ}{dmc_d}\frac{dmc_d}{d\Gamma}\frac{dq}{dmc_d}\frac{dmc_d}{d\bar{e}}$. Hence, the bracket $\left[\frac{dQ}{d\bar{e}}\frac{dq}{d\Gamma}-\frac{dQ}{d\Gamma}\frac{dq}{d\bar{e}}\right]$ is zero, and (40) is reduced to:

$$x\left[\frac{\partial w}{\partial \Gamma}\frac{\frac{dq}{d\bar{e}}}{\frac{dq}{d\Gamma}}-\frac{\partial w}{\partial \bar{e}}\right]=w(\bar{e},\Gamma)x_{\bar{e}}+d'.$$

Proposition 5 then follows directly.

Recent publications in the series Discussion Papers

279 K. Nyborg and M. Rege (2000): The Evolution of Considerate Smoking Behavior

280 M. Søberg (2000): Imperfect competition, sequential auctions, and emissions trading: An experimental evaluation

281 L. Lindholt (2000): On Natural Resource Rent and the Wealth of a Nation. A Study Based on National Accounts in Norway 1930-95

282 M. Rege (2000): Networking Strategy: Cooperate Today in Order to Meet a Cooperator Tomorrow

283 P. Boug, Å. Cappelen and A.R. Swensen (2000): Expectations in Export Price Formation: Tests using Cointegrated VAR Models

284 E. Fjærli and R. Aaberge (2000): Tax Reforms, Dividend Policy and Trends in Income Inequality: Empirical Evidence based on Norwegian Data

285 L.-C. Zhang (2000): On dispersion preserving estimation of the mean of a binary variable from small areas

286 F.R. Aune, T. Bye and T.A. Johnsen (2000): Gas power generation in Norway: Good or bad for the climate? Revised version

287 A. Benedictow (2000): An Econometric Analysis of Exports of Metals: Product Differentiation and Limited Output Capacity

288 A. Langørgen (2000): Revealed Standards for Distributing Public Home-Care on Clients

289 T. Skjerpen and A.R. Swensen (2000): Testing for long-run homogeneity in the Linear Almost Ideal Demand System. An application on Norwegian quarterly data for non-durables

290 K.A. Brekke, S. Kverndokk and K. Nyborg (2000): An Economic Model of Moral Motivation

291 A. Raknerud and R. Golombek: Exit Dynamics with Rational Expectations

292 E. Biørn, K-G. Lindquist and T. Skjerpen (2000): Heterogeneity in Returns to Scale: A Random Coefficient Analysis with Unbalanced Panel Data

293 K-G. Lindquist and T. Skjerpen (2000): Explaining the change in skill structure of labour demand in Norwegian manufacturing

294 K. R. Wangen and E. Biørn (2001): Individual Heterogeneity and Price Responses in Tobacco Consumption: A Two-Commodity Analysis of Unbalanced Panel Data

295 A. Raknerud (2001): A State Space Approach for Estimating VAR Models for Panel Data with Latent Dynamic Components

296 J.T. Lind (2001): Tout est au mieux dans ce meilleur des ménages possibles. The Pangloss critique of equivalence scales

297 J.F. Bjørnstad and D.E. Sommervoll (2001): Modeling Binary Panel Data with Nonresponse

298 Taran Fæhn and Erling Holmøy (2001): Trade Liberalisation and Effects on Pollutive Emissions and Waste. A General Equilibrium Assessment for Norway

299 J.K. Dagsvik (2001): Compensated Variation in Random Utility Models

300 K. Nyborg and M. Rege (2001): Does Public Policy Crowd Out Private Contributions to Public Goods?

301 T. Hægeland (2001): Experience and Schooling: Substitutes or Complements

302 T. Hægeland (2001): Changing Returns to Education Across Cohorts. Selection, School System or Skills Obsolescence?

303 R. Bjørnstad: (2001): Learned Helplessness, Discouraged Workers, and Multiple Unemployment Equilibria in a Search Model

304 K. G. Salvanes and S. E. Førre (2001): Job Creation, Heterogeneous Workers and Technical Change: Matched Worker/Plant Data Evidence from Norway

305 E. R. Larsen (2001): Revealing Demand for Nature Experience Using Purchase Data of Equipment and Lodging

306 B. Bye and T. Åvitsland (2001): The welfare effects of housing taxation in a distorted economy: A general equilibrium analysis

307 R. Aaberge, U. Colombino and J.E. Roemer (2001): Equality of Opportunity versus Equality of Outcome in Analysing Optimal Income Taxation: Empirical Evidence based on Italian Data

308 T. Kornstad (2001): Are Predicted Lifetime Consumption Profiles Robust with respect to Model Specifications?

309 H. Hungnes (2001): Estimating and Restricting Growth Rates and Cointegration Means. With Applications to Consumption and Money Demand

310 M. Rege and K. Telle (2001): An Experimental Investigation of Social Norms

311 L.C. Zhang (2001): A method of weighting adjustment for survey data subject to nonignorable nonresponse

312 K. R. Wangen and E. Biørn (2001): Prevalence and substitution effects in tobacco consumption. A discrete choice analysis of panel data

313 G.H. Bjertnær (2001): Optimal Combinations of Income Tax and Subsidies for Education

314 K. E. Rosendahl (2002): Cost-effective environmental policy: Implications of induced technological change

315 T. Kornstad and T.O. Thoresen (2002): A Discrete Choice Model for Labor Supply and Child Care

316 A. Bruvoll and K. Nyborg (2002): On the value of households' recycling efforts

317 E. Biørn and T. Skjerpen (2002): Aggregation and Aggregation Biases in Production Functions: A Panel Data Analysis of Translog Models

318 Ø. Døhl (2002): Energy Flexibility and Technological Progress with Multioutput Production. Application on Norwegian Pulp and Paper Industries

319 R. Aaberge (2002): Characterization and Measurement of Duration Dependence in Hazard Rate Models

320 T. J. Klette and A. Raknerud (2002): How and why do Firms differ?

321 J. Aasness and E. Røed Larsen (2002): Distributional and Environmental Effects of Taxes on Transportation

322 E. Røed Larsen (2002): The Political Economy of Global Warming: From Data to Decisions

323 E. Røed Larsen (2002): Searching for Basic Consumption Patterns: Is the Engel Elasticity of Housing Unity?

324 E. Røed Larsen (2002): Estimating Latent Total Consumption in a Household.

325 E. Røed Larsen (2002): Consumption Inequality in Norway in the 80s and 90s.

326 H.C. Bjørnland and H. Hungnes (2002): Fundamental determinants of the long run real exchange rate:The case of Norway.

327 M. Søberg (2002): A laboratory stress-test of bid, double and offer auctions.

328 M. Søberg (2002): Voting rules and endogenous trading institutions: An experimental study.

329 M. Søberg (2002): The Duhem-Quine thesis and experimental economics: A reinterpretation.

330 A. Raknerud (2002): Identification, Estimation and Testing in Panel Data Models with Attrition: The Role of the Missing at Random Assumption

331 M.W. Arneberg, J.K. Dagsvik and Z. Jia (2002): Labor Market Modeling Recognizing Latent Job Attributes and Opportunity Constraints. An Empirical Analysis of Labor Market Behavior of Eritrean Women

332 M. Greaker (2002): Eco-labels, Production Related Externalities and Trade

333 J. T. Lind (2002): Small continuous surveys and the Kalman filter

334 B. Halvorsen and T. Willumsen (2002): Willingness to Pay for Dental Fear Treatment. Is Supplying Fear Treatment Social Beneficial?

335 T. O. Thoresen (2002): Reduced Tax Progressivity in Norway in the Nineties. The Effect from Tax Changes

336 M. Søberg (2002): Price formation in monopolistic markets with endogenous diffusion of trading information: An experimental approach

337 A. Bruvoll og B.M. Larsen (2002): Greenhouse gas emissions in Norway. Do carbon taxes work?

338 B. Halvorsen and R. Nesbakken (2002): A conflict of interests in electricity taxation? A micro econometric analysis of household behaviour

339 R. Aaberge and A. Langørgen (2003): Measuring the Benefits from Public Services: The Effects of Local Government Spending on the Distribution of Income in Norway

340 H. C. Bjørnland and H. Hungnes (2003): The importance of interest rates for forecasting the exchange rate

341 A. Bruvoll, T.Fæhn and Birger Strøm (2003): Quantifying Central Hypotheses on Environmental Kuznets Curves for a Rich Economy: A Computable General Equilibrium Study

342 E. Biørn, T. Skjerpen and K.R. Wangen (2003): Parametric Aggregation of Random Coefficient Cobb-Douglas Production Functions: Evidence from Manufacturing Industries

343 B. Bye, B. Strøm and T. Åvitsland (2003): Welfare effects of VAT reforms: A general equilibrium analysis

344 J.K. Dagsvik and S. Strøm (2003): Analyzing Labor Supply Behavior with Latent Job Opportunity Sets and Institutional Choice Constraints

345 A. Raknerud, T. Skjerpen and A. Rygh Swensen (2003): A linear demand system within a Seemingly Unrelated Time Series Equation framework

346 B.M. Larsen and R.Nesbakken (2003): How to quantify household electricity end-use consumption

347 B. Halvorsen, B. M. Larsen and R. Nesbakken (2003): Possibility for hedging from price increases in residential energy demand

348 S. Johansen and A. R. Swensen (2003): More on Testing Exact Rational Expectations in Cointegrated Vector Autoregressive Models: Restricted Drift Terms

349 B. Holtsmark (2003): The Kyoto Protocol without USA and Australia - with the Russian Federation as a strategic permit seller

350 J. Larsson (2003): Testing the Multiproduct Hypothesis on Norwegian Aluminium Industry Plants

351 T. Bye (2003): On the Price and Volume Effects from Green Certificates in the Energy Market

352 E. Holmøy (2003): Aggregate Industry Behaviour in a Monopolistic Competition Model with Heterogeneous Firms

353 A. O. Ervik, E.Holmøy and T. Hægeland (2003): A Theory-Based Measure of the Output of the Education Sector

354 E. Halvorsen (2003): A Cohort Analysis of Household Saving in Norway

355 I. Aslaksen and T. Synnestvedt (2003): Corporate environmental protection under uncertainty

356 S. Glomsrød and W. Taoyuan (2003): Coal cleaning: A viable strategy for reduced carbon emissions and improved environment in China?

357 A. Bruvoll T. Bye, J. Larsson og K. Telle (2003): Technological changes in the pulp and paper industry and the role of uniform versus selective environmental policy.

358 J.K. Dagsvik, S. Strøm and Z. Jia (2003): A Stochastic Model for the Utility of Income.

359 M. Rege and K. Telle (2003): Indirect Social Sanctions from Monetarily Unaffected Strangers in a Public Good Game.

360 R. Aaberge (2003): Mean-Spread-Preserving Transformation.

361 E. Halvorsen (2003): Financial Deregulation and Household Saving. The Norwegian Experience Revisited

362 E. Røed Larsen (2003): Are Rich Countries Immune to the Resource Curse? Evidence from Norway's Management of Its Oil Riches

363 E. Røed Larsen and Dag Einar Sommervoll (2003): Rising Inequality of Housing? Evidence from Segmented Housing Price Indices

364 R. Bjørnstad and T. Skjerpen (2003): Technology, Trade and Inequality

365 A. Raknerud, D. Rønningen and T. Skjerpen (2003): A method for improved capital measurement by combining accounts and firm investment data

366 B.J. Holtsmark and K.H. Alfsen (2004): PPP-correction of the IPCC emission scenarios - does it matter?

367 R. Aaberge, U. Colombino, E. Holmøy, B. Strøm and T. Wennemo (2004): Population ageing and fiscal sustainability: An integrated micro-macro analysis of required tax changes

368 E. Røed Larsen (2004): Does the CPI Mirror Costs.of.Living? Engel's Law Suggests Not in Norway

369 T. Skjerpen (2004): The dynamic factor model revisited: the identification problem remains

370 J.K. Dagsvik and A.L. Mathiassen (2004): Agricultural Production with Uncertain Water Supply

371 M. Greaker (2004): Industrial Competitiveness and Diffusion of New Pollution Abatement Technology – a new look at the Porter-hypothesis