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Strategic Climate Policy in Small, Open Economies

Abstract:

According to environmental interests groups governments should use their climate policy strategically in order to provide for a faster introduction of new, cleaner technologies. Strategic use of climate policy could also induce the development of a successful upstream abatement technology industry like the Danish windmill industry. Interestingly, this latter question has not been analyzed theoretically before. Our point of departure is a three-stage game between a government in a small country with a climate restriction, and a limited number of firms supplying carbon abatement technology. The government moves first, and may use its climate policy strategically to influence the behavior of the upstream technology firms. An especially stringent climate policy towards the polluting downstream sector may then in fact be well founded. It will increase the competition between the technology suppliers, and lead to lower domestic abatement costs. However, to our surprise, a strict environmental policy is not a particularly good industrial policy with respect to developing new successful export sectors.

Keywords: Strategic climate policy; Abatement technology; Small, open economies

JEL classification: O32, Q2, Q25

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1 Introduction

Stabilization of greenhouse gas concentrations in the atmosphere at desirable levels will require large reductions in carbon emissions from energy production in the coming decades. Such large reductions will not be achievable without developing carbon-free energy technologies. In order to achieve their emission targets, open economies will likely rely on the global technology frontier just as much as on their own research effort. The dependency on the global technology level is frequently used as a rationale for focusing on technology adoption rather than funding domestic R&D on new technologies. On the other hand, a stringent climate policy or support to environmental R&D could stimulate the emergence of new, profitable export niches. The Danish windmill industry is often put forward as an example of the latter, and in Norway similar arguments are used in connection with carbon capture technology from gas power plants.

In this paper we explicitly include the export potential of new technologies in our evaluation of climate policies. In particular, we consider the claim that governments acting strategically should set a more strict climate policy than other countries in order to spur a pollution abatement export sector within their country. In most signatory countries to the Kyoto treaty the governments currently control the buying and selling of carbon emission allowances on the international market. The governments are therefore in principle able to enforce a higher domestic shadow price on carbon emissions than the international quota price. Further, we also evaluate an R&D subsidy to new abatement technologies as part of the optimal policy mix.

Based on theoretical as well as numerical analyses, we conclude that enforcing a more stringent climate policy than other countries may in fact be well founded. It will increase the competition between the technology suppliers, and lead to lower domestic abatement costs. However, to our surprise, a strict environmental policy is not a particularly good industrial policy with respect to developing new successful export sectors. Since carbon abatement technology is a traded good, the foreign pollution abatement industry also responds to a stricter national environmental policy. Hence, the national pollution abatement industry will not gain any competitive advantage on the foreign pollution abatement industry.

Matters are different with respect to supporting environmental R&D. As opposed to a stringent climate policy, an R&D subsidy unambiguously spurs the export performance of the domestic technology firm on behalf of the foreign firms, although our numerical simulations indicate that this effect is small. As interestingly, in the numerical simulations we also find that a subsidy program is complimentary to a stringent climate policy. Hence, with respect to abatement technologies, technology push programs should not be launched as an alternative to market pull strategies, but rather as a complement.

There already exists a well developed strand of theoretical literature analyzing strategic use of environmental policy, see for example Barrett[3] and Rauscher [17]. Parts of this literature also include strategic environmental R&D conducted by the polluting firms themselves as a response to environmental policy, see Ulph[21] and Ulph[22]. The main findings in this literature are that the incentive to use environmental policy strategically depends on the form of downstream competition and the availability of other governmental policy instruments. For instance, in Barrett[3] it is shown that an export subsidy completely removes the incentive to use environmental policy strategically. Further, while Cournot competition downstream generally calls for a weak environmental policy, Bertrand competition downstream calls for the opposite, namely an especially stringent environmental policy. The inclusion of R&D conducted by the polluting firms does not radically change this picture. According to Ulph[21] and Ulph[22], it introduces a new incentive for acting strategically, that is, the government may try to influence the foreign level of environmental R&D. However, the direction of this effect is ambiguous, and it may reinforce the incentive to set a weak policy under Cournot competition, and *vice-versa* under Bertrand competition.

The literature on strategic use of environmental policy has until now focused entirely on the competitiveness of the downstream polluting industries themselves, but in this paper we shift focus to an upstream abatement technology industry, serving both domestic and foreign polluting firms. The analysis reveals a new strategic effect which we coin the *price effect*. In order to obtain lower prices on abatement equipment, the government commits to an especially stringent environmental standard inducing a higher elasticity of demand for abatement technology. This lowers the price through a lower markup on costs for the suppliers of the technology.

That environmental policy may have a *price effect* is backed by the experience with 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 leads 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 the thousandth of a dollar) 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 scrubbing measured as emission reduction per \$.

Moreover, the inclusion of an environmental R&D subsidy does not remove the *price effect* and the incentive to use environmental policy strategically as is the case for an export/production subsidy in the strategic environmental policy literature. Rather, they seem to reinforce each other, that is, a strin-

gent environmental policy makes the market for abatement technology larger, which again increases the benefits from an environmental R&D subsidy.

The Danish windmill industry is often put forward as an example of a successful combination of environmental and industrial policy. In order to reduce the carbon content of their energy supply, the Danes have heavily supported their domestic windmill industry through both proportional standards for clean energy production, and various kinds of subsidies. The Danish windmill industry has become one of the dominant actors in the world market for windmills. However, the viability of the different policy measures in welfare terms has been questioned by economists. Jespersen[9] concludes that neither the investment nor the production subsidy has been welfare enhancing in terms of induced domestic cost savings. Further, based on a CGE model for Denmark, Rasmussen[16] shows that further Danish subsidies to the production of wind power are likely to have limited cost saving effects, and thus also, a questionable welfare effect. On the other hand, neither Jespersen[9] nor Rasmussen[16] take into account the potential for strategic trade policy.

With respect to climate policy and carbon abatement, a particularly interesting new abatement technology is carbon capture and storage (CCS). According to a recent OECD study [15], a major share of future electricity production will be from coal and gas power plants with CCS. Sensitivity analyses carried out in the same study taking into account for instance increased competitiveness of renewables, suggests that, overall, CCS is a robust option from a cost effectiveness perspective. In the paper we supplement our theoretical analysis with numerical simulations based on hypothetical future markets for carbon capture technologies.¹ The effects of activist trade policies have often been shown to be welfare reducing instead of improving, or have been shown to have a very modest effect, see for example Venables [23]. When our results are more encouraging with respect to an activist policy, i.e., subsidies to environmental R&D in combination with an especially stringent climate policy, it is mainly due to the effect on domestic carbon abatement costs, and to a lesser degree improved export performance.

With respect to the other literature on research and development of new pollution abatement techniques, it has mainly focused on instrument choice such as the choice between tradeable emission quotas and emission taxes, see for instance Downing and White[6], Jung et al.[10] and Requate and Unold[18]. In these contributions environmental R&D either happens within the polluting firm, or the polluting firm can buy the right to use the innovation to a fixed price. However, imperfect competition is likely to be central to any innovation process. Firms will only be willing to take the risk of spending research and development costs, if they can for some time enjoy oligopoly rents, see for instance Romer[19] for his seminal work on competition in an R&D sector. As far as we know, this is the first contribution that explicitly takes imperfect competition in the R&D sector into account while analyzing climate

¹In contrast, most former numerical studies of strategic trade policy is conducted on historical, real market data, see for example Baldwin and Krugman[2].

policy and its effect on the development of new abatement technologies.

2 The model

The model used in the paper is a three stage game between a government in a small country and a limited number of upstream firms supplying abatement technology. The government moves first, and may use its climate policy strategically to influence the behavior of the upstream firms.

Our point of departure is the reciprocal-dumping model, see Brander and Krugman[5]. There are two separate output markets; one in a small country A and one in a large region B. In the first stage of the game the government in A sets a national carbon emission target for its polluting output industry, taking as given the carbon emission target of B and the international quota price on carbon emissions. Then, in the second stage the firms offering abatement technology decide on the amount of R&D², which will reduce the cost of supplying the technology to the output industry in a deterministic manner. Finally, in the third stage the technology firms compete to supply abatement technology to the output industry both in the small country and in the large region. In the first part of our analyses (Section 2 and 3), however, we disregard stage 2, and look at policy implications when costs of producing the technology are given.

We assume that environmental policy become simultaneously known in both regions at some point of time τ_0 , and that it comes into play at a future point of time $\tau_0 + \Delta\tau$. The R&D is conducted in the intermediate period $\Delta\tau$.

In the rest of the analyses we will speak of the output market as the electricity market, and the abatement technology as carbon capture and storage (CCS).³ However, the results may of course be generalized to other markets and abatement technologies, as long as the assumptions make sense (e.g., separate output markets).

2.1 Carbon emissions

Let emission e_i of CO_2 from the electricity industry in the period following $\tau_0 + \Delta\tau$ be given:

$$e_i = e_i(q_i, x_i), \quad i = a, b, \quad (1)$$

where q_i is electricity production of a representative firm in region i and x_i denotes the carbon capture effort of the representative firm in region i . We assume that the emission function is homogeneous of degree 1 in q_i and x_i ,

²By R&D we also mean demonstration projects, where the main objective is to obtain experience and reduce costs, and not to produce technology services (this is sometimes referred to as RD&D - Research, Development and Demonstration - in the literature).

³We assume that coal-fired plants (in particular Integrated Gasification Combined Cycle - IGCC) and gas-fired plants (Combined Cycle Gas Turbine electricity generation - CCGT) with CCS are the only technologically feasible carbon free energy technologies for large scale power installations. This implies that we do not model the competition between CCS and other carbon free energy technologies such as renewables or nuclear.

and that the derivatives have the following characteristics: $\frac{\partial e_i}{\partial q_i} > 0$, $\frac{\partial^2 e_i}{(\partial q_i)^2} \geq 0$, $\frac{\partial e_i}{\partial x_i} \leq 0$, $\frac{\partial^2 e_i}{(\partial x_i)^2} > 0$. These assumptions imply e.g. that for a given carbon capture effort, emissions per unit of output are increasing in output, and that emission per unit of output is homogeneous of degree zero in output and capture effort.

We assume that the governments in each jurisdiction formulate their jurisdiction specific target for carbon emissions from the electricity industry as a proportional standard. We do not go into detail on how the targets are reached, i.e., by direct regulation of power utilities, by quota markets with free allowances based on benchmarking (cf. the rules for new entrants in the EU Emission Trading Scheme), or by green certificate markets including CCS as a "green" technology. Instead we concentrate on the upstream effects of environmental policy.

Denote the level of standard in region i by r_i such that $r_i = 1 - \frac{e_i}{q_i}$, i.e., a higher r_i implies a smaller proportional standard. The necessary amount of carbon capture effort to reach the jurisdiction specific target is then given:

$$x_i = \hat{x}_i(r_i, q_i) \quad (2)$$

where the derivatives fulfil $\frac{\partial \hat{x}_i}{\partial r_i} \geq 0$, $\frac{\partial \hat{x}_i}{\partial q_i} > 0$.⁴ Since the emission function is homogeneous of degree 1, we can reformulate (2) to:

$$x_i = \hat{x}_i(r_i, q_i) = x_i(r_i)q_i, \quad (3)$$

where $\frac{\partial x_i}{\partial r_i} \geq 0$, $\frac{\partial^2 x_i}{(\partial r_i)^2} \geq 0$.

Denote carbon storage efforts by y_i . Clearly, carbon capture and carbon storage are compliments, which implies $y_i = x_i$. The total cost of the representative electricity firm can then be expressed:

$$c_i^{tot}(q_i) = c_0 q_i + (w_i + v_i)x_i(r_i)q_i, \quad (4)$$

where c_0 is the marginal cost ex carbon abatement of power production, and where w_i is the jurisdiction specific price of CO_2 capture, v_i is the jurisdiction specific price of CO_2 storage. Note that the constant marginal cost of the representative electricity producer implies zero profit.

Let p_a denote the electricity price in Country A and p_b the electricity price in Region B. Demand for electricity in each jurisdiction is given by the following demand functions:

$$q_i = q_i(p_i), \quad (5)$$

where $q_i' < 0$.

The constant marginal cost of the representative electricity producer implies that the power price is given from supply, while power production is given

⁴We have $(1 - r_i) = \frac{e_i(q_i, x_i)}{q_i}$, which can be inverted to yield $x_i = x_i(r_i, q_i)$. The signs on the first order derivatives follow from total differentiation of the equation $(1 - r_i) = \frac{e_i(q_i, x_i)}{q_i}$. We must have $\frac{\partial e_i}{\partial q_i} > (1 - r_i)$ in order to have $\frac{\partial x_i}{\partial q_i} > 0$.

from demand. With respect to consumer surplus, we have $CS_i = CS_i(q_i)$ with $CS'_i \geq 0$, i.e., that consumer surplus increases in output.

2.2 The demand for carbon capture

We will now derive the demand function for carbon capture in each region. First, we need to solve for the optimal quantity of electricity production. In equilibrium the electricity price must be equal to the marginal cost of electricity: $p_i = c_0 + (w_i + v_i)x_i(r_i)$. From the demand function (5) we then have:

$$q_i = q_i(c_0 + (w_i + v_i)x_i(r_i)), \quad (6)$$

which gives the size of power production in each jurisdiction.

From (3) we have that total demand for carbon capture x is:

$$x_i = x_i(r_i)q_i = x_i(r_i)q_i(c_0 + (w_i + v_i)x_i(r_i)), \quad (7)$$

The function (7) is the demand function for carbon capture in each jurisdiction. While we assume that the price of carbon storage is given, and dependent on local conditions in each region, the price of carbon capture is endogenous and dependent on demand and supply. Of great interest is then how the elasticity of demand depends on the climate policy:

Lemma 1 *For all concave or iso-elastic demand functions, the price elasticity of demand for carbon capture is increasing in the emission standard, that is, $\left| \frac{\partial El_{x_i, w_i}}{\partial r_i} \right| > 0$.*

Proof. The elasticity of demand is given:

$$El_{x_i, w_i} = \frac{x_i(r_i)w_i \frac{\partial q_i}{\partial p_i}}{q_i(c_i + (w_i + v_i)x_i(r_i))}$$

and its derivative with respect to the level of regulation:

$$\frac{\partial El_{x_i, w_i}}{\partial r_i} = w_i \frac{\partial x_i}{\partial r_i} \frac{q_i \frac{\partial q_i}{\partial p_i} - (w_i + v_i)x_i(r_i) \left[\left(\frac{\partial q_i}{\partial p_i} \right)^2 - q_i \frac{\partial^2 q_i}{\partial p_i^2} \right]}{[q_i(c_i + (w_i + v_i)x_i(r_i))]^2}$$

which is negative as long as $\frac{\partial^2 q_i}{\partial p_i^2} \leq 0$. Observe that $(w_i + v_i)x_i(r_i) < p_i$ since $c_i > 0$. Hence, if $\frac{\partial^2 q_i}{\partial p_i^2} > 0$, a sufficient, but not necessary condition is: $\left| q_i \frac{\partial q_i}{\partial p_i} \right| \geq -p_i \left[\left(\frac{\partial q_i}{\partial p_i} \right)^2 - q_i \frac{\partial^2 q_i}{\partial p_i^2} \right]$, which always holds with " = " for the demand function $q_i = \alpha p_i^{-\beta}$. ■

When meeting the emission target, the representative firm chooses between reducing output and investing in pollution abatement equipment. For instance, if the firm has m plants and none with carbon capture, it will have

to buy some carbon capture technology in order to comply with a proportional standard. However, if one or more plants already have installed carbon capture technology, the firm can also respond by reducing output from the plants that haven't installed such technology. Consequently, as climate policy gets increasingly stringent, the representative firm will on the margin be more prone to reduce output, and more reluctant to invest in carbon capture equipment. This effect explains why the price elasticity increases. In the rest of the paper we restrict attention to demand functions $q_i(p_i)$ for which Lemma 1 applies.

2.3 The supply of carbon capture

We are then able to look at the supply of carbon capture. We assume that there is one firm in Country A and one firm in Region B that supply carbon capture equipment.⁵ Both firms supply their home market as well as the foreign market. Thus, total supply of carbon capture equipment in country A x_a is $x_a^h + x_a^f$, while total supply of carbon capture in region B x_b is $x_a^f + x_b^h$. Note that x_i^h denotes the supply of a carbon capture firm in jurisdiction i to its home market, and that x_i^f denotes the supply of a firm in jurisdiction i to its export market (i.e., jurisdiction $-i$).⁶

Supply of carbon capture takes place to a constant marginal cost ρ_i , which in turn may be dependent of the amount of research z_i done by firm i in a former period. We will return to the R&D game in Section 4. Further, we assume that there is a trade cost t associated with supplying the foreign market.⁷

The demand for carbon capture is described by (7), which can be inverted to yield: $w_i(x_i, r_i) = \frac{1}{x_i(r_i)} p_i\left(\frac{x_i}{x_i(r_i)}\right) - \frac{c_0}{x_i(r_i)} - v_i$. where $p_i(\cdot)$ is the inverse of $q_i(\cdot)$. In the market game the carbon capture firm in jurisdiction i maximizes:

$$\max \pi_i = \left[w_i \left(x_i^h + x_{-i}^f, r_i \right) - \rho_i \right] x_i^h + \left[w_{-i} \left(x_{-i}^h + x_i^f, r_{-i} \right) - \rho_i - t \right] x_i^f, \quad (8)$$

We look for a Cournot-Nash solution in each market. The first-order conditions from the profit expressions yield two *independent* sets of two equations for the four unknown outputs of carbon capture technology:

⁵In the simulations presented later, we expand the model with more firms in Region B.

⁶If $i = a$, then $-i = b$ and *vice-versa*.

⁷One reason for the trade cost could be differences in technology between the two upstream firms, e.g., that the large region firm mainly focuses on coal-fired power plants while the small country firm mainly focuses on gas-fired power plants. According to OECD[15] both type of plants will be equipped with carbon capture in future climate policy scenarios, however, the respective capture technologies are more or less different.

$$\begin{aligned}\frac{\partial \pi_a}{\partial x_a^h} &= \frac{\partial w_a(x_a^h + x_b^f, r_a)}{\partial x_a^h} x_a^h + w_a - \rho_a = 0 \quad \& \\ \frac{\partial \pi_b}{\partial x_b^f} &= \frac{\partial w_a(x_a^h + x_b^f, r_a)}{\partial x_b^f} x_b^f + w_a - \rho_b - t = 0\end{aligned}\tag{9}$$

$$\begin{aligned}\frac{\partial \pi_a}{\partial x_a^f} &= \frac{\partial w_b(x_a^f + x_b^h, r_b)}{\partial x_a^f} x_a^f + w_b - \rho_a - t = 0 \quad \& \\ \frac{\partial \pi_b}{\partial x_b^h} &= \frac{\partial w_b(x_a^f + x_b^h, r_b)}{\partial x_b^h} x_b^h + w_b - \rho_b = 0\end{aligned}\tag{10}$$

Thus, we can write the Cournot-Nash solutions to the two market games as follows:

$$x_i^h = x_i^h(\rho_a, \rho_b, r_i), \quad x_i^f = x_i^f(\rho_a, \rho_b, r_{-i}),\tag{11}$$

Note that the levels of regulation r_i and r_{-i} do not appear together. With respect to export output, we therefore get the following remark:

Remark 2 For a given cost of carbon capture ρ_i , a higher environmental standard r_i will have no effect on the export output of carbon capture equipment from region i , i.e. $\frac{\partial x_i^f}{\partial r_i} = 0$.

However, for the policy maker, it is also of great interest how the price of carbon capture is affected by the level of regulation. The price on carbon capture w_i is given from $w_i = w_i(x_i^h(\rho_a, \rho_b, r_i) + x_i^f(\rho_a, \rho_b, r_i), r_i)$. Consequently, the price on carbon capture is influenced by the level of regulation in jurisdiction i through two channels; directly by affecting the demand function for carbon capture technology, and indirectly by affecting the Nash-equilibrium outputs. We have the following proposition:

Proposition 3 For given marginal costs of carbon capture ρ_i, ρ_{-i} , the price of carbon capture equipment w_i is decreasing in the emission standard r_i , i.e. $\frac{dw_i}{dr_i} < 0$.

Proof. The equations in (9) and (10) can be rewritten according to:

$$\frac{w_i - \rho_i}{w_i} = \frac{x_i^h / (x_i^h + x_{-i}^f)}{|El_{x_i, w_i}|} \quad \& \quad \frac{w_i - \rho_{-i} - t}{w_i} = \frac{x_{-i}^f / (x_i^h + x_{-i}^f)}{|El_{x_i, w_i}|}.$$

By Lemma 1 we know that the elasticity of demand is increasing in the emission standard r_i . Hence, at least one of the right hand sides of the expressions above will decrease, and consequently the left hand side in that expression has to decrease. Since $\frac{d(\frac{w-\rho}{w})}{dw} > 0$, the price has to decrease. ■

Proposition 3 is an application of a well known result from general Cournot analysis i.e. that the firms' margin over costs decreases if the elasticity of demand increases, see for example Vives[24], page 100.

It will also be of interest how x_i^h and x_{-i}^f respond to a strengthening of climate policy r_i . It turns out that it is hard to get unambiguous results for $\frac{\partial x_i^h}{\partial r_i}$ and $\frac{\partial x_{-i}^f}{\partial r_i}$. It seems reasonable to assume $\frac{\partial x_i^h}{\partial r_i} > 0$ i.e. a stricter climate target in jurisdiction i will increase the output of carbon capture equipment from the upstream firm in jurisdiction i . This assumption is confirmed in our numerical simulations⁸. It then follows that $\frac{\partial x_{-i}^f}{\partial r_i} > 0$ as long as $x_i^h \approx x_{-i}^f$ and $\frac{\partial x_{-i}^f}{\partial r_i} < 0$ if $x_i^h \gg x_{-i}^f$ (see Appendix A).

3 Optimal environmental policy in Country A without R&D

We assume that each region has entered into an international agreement, which has put a ceiling on total emissions of carbon. Further, we assume that Country A is free to trade in carbon emissions to a fixed quota price of ϵ . In particular, we assume that the government controls the total amount of emission trading across the border such that marginal abatement cost may differ across jurisdictions.

For Country A welfare is then given:

$$W_a = CS_a(q_a) - \epsilon(1 - r_a)q_a + \left[w_a \left(x_a^h(r_a) + x_b^f(r_a), r_a \right) - \rho_a \right] x_a^h(r_a) \quad (12)$$

$$+ \left[w_b \left(x_b^h(r_b) + x_a^f(r_b), r_b \right) - \rho_a - t \right] x_a^f(r_b),$$

where the first term is consumer surplus expressed as a function of total electricity output, the second term is residual emissions times the quota price, the third term is the profit of the domestic carbon capture firm obtained in the domestic market and finally, the fourth term is the profit of the domestic carbon capture firm obtained in the foreign market. Note that we have suppressed ρ_a and ρ_b from x_i^h and x_i^f since these are given. Finally, we assume that carbon storage can be carried out to a fixed price, and that there is zero profit in this activity.

The first-order condition is:

$$\frac{\partial W_a}{\partial r_a} = CS'_a \frac{\partial q_a}{\partial r_a} - \epsilon \left[(1 - r_a) \frac{\partial q_a}{\partial r_a} + q_a \right] + [CS'_a - \epsilon(1 - r_a)] \frac{\partial q_a}{\partial w_a} \frac{dw_a}{dr_a} \quad (13)$$

$$+ \left[\frac{\partial w_a}{\partial x_a^h} x_a^h(r_a) + w_a - \rho_a \right] \frac{\partial x_a^h}{\partial r_a} + \left[\frac{\partial w_a}{\partial r_a} + \frac{\partial w_a}{\partial x_b^f} \frac{\partial x_b^f}{\partial r_a} \right] x_a^h(r_a) = 0.$$

⁸Two sufficient, but not necessary, conditions for the assumption to hold in the general case are given in Appendix A.

We assume that $\frac{\partial^2 W_a}{\partial (r_a)^2} < 0$, and hence, that a maximum exists. The first term in (13) is the loss in consumer surplus due to a more stringent climate policy, while the second term is the savings in emission quota expenditures due to a more stringent policy. The third term is the net benefit from a lower price on carbon capture technology. The next term $\left[\frac{\partial w_a}{\partial x_a^h} x_a^h(r_a) + w_a - \rho_a \right] \frac{\partial x_a^h}{\partial r_a}$ is the effect on the carbon capture firm's profit from changes in its own output of carbon capture technology. Since the firm has set its output optimally, the effect is zero, see the first order condition (9). The last term is the effect on the carbon capture firm's profit from changes in the demand function for carbon capture technology and from changes in the foreign output of carbon capture technology. In other words, there are two strategic effects; a price effect $[CS' - \varepsilon(1 - r_a)] \frac{\partial q_a}{\partial w_a} \frac{dw_a}{dr_a}$ and a rent effect $\left[\frac{\partial w_a}{\partial r_a} + \frac{\partial w_a}{\partial x_b^f} \frac{\partial x_b^f}{\partial r_a} \right] x_a^h(r_a)$ confined to the domestic market.

Our benchmark is the textbook rule for optimal environmental policy, i.e., *marginal abatement cost* should equal *the quota price*. If the welfare maximizing environmental policy diverts from the textbook rule, we will say that environmental policy is *weak/stringent* depending on whether *marginal abatement cost* is lower/higher than *the quota price*. Setting the two strategic effects equal to zero, we obtain for the textbook rule:

$$\varepsilon = \frac{-CS' \frac{\partial q_a}{\partial r_a}}{\left[q_a - (1 - r_a) \frac{\partial q_a}{\partial r_a} \right]}. \quad (14)$$

The term in the numerator is the change in consumer surplus (keeping the price w_a constant), while the term in the denominator is the change in emissions (again keeping the price w_a constant). Since there is constant returns to scale in electricity production, there is no loss in producer surplus from this sector. We will refer to the emission standard that fulfills (14) by r_a^0 .

From (13), as long as the two strategic effects equal zero, we must have $[CS' - \varepsilon(1 - r_a^0)] > 0$ (since $\frac{\partial q_a}{\partial r_a} < 0$). Further, this inequality must also hold when *marginal abatement cost* exceeds *the quota price*, due to the concavity of $W_a(r_a)$. Thus, the price effect is positive when policy is set at the textbook rule or stronger (both $\frac{\partial q_a}{\partial w_a}$ and $\frac{dw_a}{dr_a}$ are negative).

The first part of the rent effect is negative since for a given output on carbon capture technology, the price on carbon capture technology falls. The second part depends on the term $\frac{\partial x_b^f}{\partial r_a}$, that is, in what direction the foreign carbon capture firm will change its output as a response to a more stringent climate policy. When trade costs are small, it seems reasonable to assume that it is positive, and hence the rent effect will be negative. We then have that a stringent climate policy both lowers the domestic price on carbon capture and induces the foreign firm to increase its output in the domestic market, which both on the margin hurts the domestic firm. Our findings are summarized in the following proposition:

Proposition 4 *A small, open economy may have incentives to set an especially stringent environmental policy. However, only one of the two mentioned strategic effects pulls unambiguously in this direction:*

1. *A strict emission standard will make carbon abatement cheaper. This is the price effect, which pulls unambiguously in the direction of a more stringent policy.*
2. *A strict emission standard may reduce the abatement industry's ability to extract rents in its domestic market. This is the rent effect, which may pull in the direction of a weaker policy.*

Note that the export market plays no role in the setting of the optimal climate policy. This, however, change when we include environmental R&D.

4 Including environmental R&D

We now include R&D in the model by assuming that the marginal costs of carbon capture are determined by the amount of R&D done by the carbon capture firms. Let $\rho_i = \rho(z_i)$ in which z_i is the total level of carbon capture R&D expenditures in jurisdiction i . For the derivatives of ρ we have; $\rho' < 0$ and $\rho'' \geq 0$. Further, let $(1 - \zeta_i)z_i$ denote the private cost of R&D in jurisdiction i where ζ_i is the region specific subsidy rate. Clearly, results from R&D done by one firm could sometimes be utilized by the other carbon capture firm, and hence, influence the marginal cost of carbon capture in that region. This is often coined a spill-over, or a positive R&D externality, and we return to this issue in a companion paper [8].

We apply the closed loop solution concept, see Tirole, chapter 8[?]. In the stage before the market game, the two carbon capture firms maximize their profit with respect to z_i taking into account how the level of R&D affects their profit in the market game:

$$\begin{aligned} \max_{z_i} \omega_i &= \left[w_i \left(x_i^h + x_{-i}^f, r_i \right) - \rho_i(z_i) \right] x_i^h \\ &+ \left[w_{-i} \left(x_{-i}^h + x_i^f, r_{-i} \right) - \rho_i(z_i) - t \right] x_i^f - (1 - \zeta_i)z_i, \end{aligned}$$

where ω_i denotes the profits of the two carbon capture firms after R&D expenditures, and where $x_i^h = x_i^h(\rho_a(z_a), \rho_b(z_b), r_i)$ and $x_i^f = x_i^f(\rho_a(z_a), \rho_b(z_b), r_{-i})$. From general Cournot theory we have $\frac{\partial x_i^h}{\partial \rho_i} \leq 0$, $\frac{\partial x_{-i}^f}{\partial \rho_i} \leq 0$ and $\frac{\partial x_i^h}{\partial \rho_{-i}} \geq 0$, $\frac{\partial x_{-i}^f}{\partial \rho_{-i}} \geq 0$.

The two first-order conditions are:

$$\frac{\partial \omega_i}{\partial z_i} = \left[\frac{\partial w_i}{\partial x_{-i}^f} \frac{\partial x_{-i}^f}{\partial \rho_i} x_i^h + \frac{\partial w_{-i}}{\partial x_{-i}^h} \frac{\partial x_{-i}^h}{\partial \rho_i} x_i^f \right] \frac{\partial \rho_i}{\partial z_i} - \left[x_i^h + x_i^f \right] \frac{\partial \rho_i}{\partial z_i} - (1 - \zeta_i) = 0, \quad (15)$$

where the terms $\left(\frac{\partial w_i}{\partial x_i^h} x_i^h + w_i - \rho_i(z_i)\right) \frac{\partial x_i^h}{\partial \rho_i} \frac{\partial \rho_i}{\partial z_i} + \left(\frac{\partial w_{-i}}{\partial x_i^f} x_i^f + w_{-i} - \rho_i(z_i) - t\right) \frac{\partial x_i^f}{\partial \rho_i} \frac{\partial \rho_i}{\partial z_i}$ have been eliminated since by (9) and (10) they are both equal to zero.

The first term in (15) is the strategic effect of R&D expenditures. Since $\frac{\partial \rho_i}{\partial z_i} < 0$, $\frac{\partial x_{-i}^f}{\partial \rho_i}, \frac{\partial x_{-i}^h}{\partial \rho_i} > 0$ and $\frac{\partial w_i}{\partial x_{-i}^f}, \frac{\partial w_{-i}}{\partial x_{-i}^h} < 0$, the strategic effect is positive. Thus, both firms act strategically, and tends to over-invest in R&D in order to gain marketshare in the subsequent market game. The two other terms are the marginal savings from R&D in the costs of producing carbon capture technology with a given carbon abatement effect and the marginal cost of R&D itself.

The two first-order conditions determine the Nash-equilibrium levels of R&D in the second stage of the game. Assuming that the second-order conditions for profit maximum hold, and that the uniqueness condition for the Nash equilibrium is met, R&D levels can be written as; $z_i = z_i(r_i, r_{-i}, \zeta_i, \zeta_{-i})$ for $i = a, b$. In order to find the signs on the derivatives of the function $z_i = z_i(r_i, r_{-i}, \zeta_i, \zeta_{-i})$, we differentiate the system (15) (see Appendix B). This results in the following table of effects:

Table I. Comparative statics of the R&D Nash-equilibrium

$$\frac{dz_i}{dr_i} \geq 0; \quad \frac{dz_i}{dr_{-i}} \geq 0; \quad \frac{dz_i}{d\zeta_i} > 0; \quad \frac{dz_i}{d\zeta_{-i}} < 0;$$

When $z_a = z_b$, we have $\frac{dz_i}{dr_i} > 0$. In Appendix B we further argue that it is reasonable to assume $\frac{dz_i}{dr_i} > 0$ for $z_a \neq z_b$. The derivative $\frac{dz_i}{dr_{-i}}$ cannot be signed even in the special case when $z_a = z_b$. However, for a low trade cost t (compared to the price) we likely have $\frac{dz_i}{dr_{-i}} > 0$, see Appendix B. This conjecture is confirmed in the numerical simulations.

Note that the effects of an R&D subsidy are unambiguous, even in the general case. An R&D subsidy gives more environmental R&D at home, and less environmental R&D abroad. We also have the following proposition:

Proposition 5 *The price on carbon capture equipment w_i is decreasing in the R&D subsidy ζ_i i.e. $\frac{\partial w_i}{\partial \zeta_i} < 0$ and in the environmental policy instrument r_i i.e. $\frac{\partial w_i}{\partial r_i} < 0$.*

Proof. See Appendix C. ■

Hence, Proposition 3 continues to hold for the case with environmental R&D. A more stringent environmental standard now has two desirable effects; I) It increases the elasticity of demand, lowering the markup over costs in the Nash-equilibrium and II) It increases the R&D effort of both firms, leading to lower production costs for carbon capture equipment.

An R&D subsidy leads to more environmental R&D in the domestic firm and less environmental R&D in the foreign firm. The former effect is stronger than the latter effect, and hence the price on carbon capture falls due to lower costs for the domestic firm.

4.1 The effect of environmental policy on export output

Before we proceed, we take a look at how environmental policy and the R&D subsidy influences export output. Export output is given:

$$x_i^f = x_i^f(\rho_i(z_i(r_i, r_{-i}, \zeta_i, \zeta_{-i})), \rho_{-i}(z_{-i}(r_i, r_{-i}, \zeta_i, \zeta_{-i})), r_{-i}).$$

The derivative of this function with respect to the environmental standard at home is given:

$$\frac{\partial x_i^f}{\partial r_i} = \frac{\partial x_i^f}{\partial \rho_i} \rho'_i(z_i) \frac{dz_i}{dr_i} + \frac{\partial x_i^f}{\partial \rho_{-i}} \rho'_{-i}(z_{-i}) \frac{dz_{-i}}{dr_i}. \quad (16)$$

Since we assume $\frac{dz_a}{dr_a} > 0$, the first term in (16) is unambiguously positive, while the second term depends on the sign of $\frac{dz_{-i}}{dr_i}$. If $\frac{dz_{-i}}{dr_i}$ is positive, which is probable with low trade barriers, the second term is negative. Hence, the total effect on export output is ambiguous. The intuition is that a higher environmental standard at home also makes environmental R&D more profitable for the foreign carbon capture firm. Hence, the home firm will meet tougher competition on its export market.

Then, with respect to the R&D subsidy at home:

$$\frac{\partial x_i^f}{\partial \zeta_i} = \frac{\partial x_i^f}{\partial \rho_i} \rho'_i(z_i) \frac{dz_i}{d\zeta_i} + \frac{\partial x_i^f}{\partial \rho_{-i}} \rho'_{-i}(z_{-i}) \frac{dz_{-i}}{d\zeta_i}. \quad (17)$$

For this derivative, both terms are unambiguously positive. An R&D subsidy makes the home firm do more environmental R&D. Since R&D levels are strategic substitutes, the foreign firm does less environmental R&D. Consequently, the home firm increases its export market share.

The following proposition sums up the results:

Proposition 6 *A higher environmental standard r_i will have an ambiguous effect on the export output of carbon capture equipment from region i i.e. $\frac{\partial x_i^f}{\partial r_i} \leq 0$, while an environmental R&D subsidy ζ_i will have an unambiguous positive effect on the export output of carbon capture equipment from region i i.e. $\frac{\partial x_i^f}{\partial \zeta_i} > 0$.*

Hence, an especially stringent environmental standard is likely not a particularly good industrial policy as long as the only purpose is to develop new successful export sectors.

5 Optimal environmental policy in Country A with R&D

When we include environmental R&D, the welfare for Country A is given (cf. 12):

$$W_a = CS_a(q_a) - \varepsilon(1 - r_a)q_a + \left[w_a (x_a^h + x_b^f, r_a) - \rho_a(z_a) \right] x_a^h \quad (18)$$

$$+ \left[w_b (x_b^h + x_a^f, r_b) - \rho_a(z_a) - t \right] x_a^f - (1 - \zeta_a)z_a - \zeta_a z_a.$$

With respect to (18), the terms have the same interpretation as in (12) apart from the two last terms, which denotes the firm's R&D cost and the government's R&D subsidy costs, respectively.⁹

We assume that $\frac{\partial^2 W_a}{\partial (r_a)^2}, \frac{\partial^2 W_a}{\partial (\zeta_a)^2} < 0$, and hence, that a maximum exists. First, we look at the optimal environmental standard, given the R&D subsidy. The first-order condition is now given (cf. 13):

$$\frac{\partial W_a}{\partial r_a} = CS' \frac{\partial q_a}{\partial r_a} + \varepsilon \left[q_a - (1 - r_a) \frac{\partial q_a}{\partial r_a} \right] \quad (19)$$

$$+ [CS' - \varepsilon(1 - r_a)] \frac{\partial q_a}{\partial w_a} \frac{\partial w_a}{\partial r_a} + \left(\frac{\partial w_a}{\partial r_a} + \frac{\partial w_a}{\partial x_b^f} \frac{\partial x_b^f}{\partial r_a} \right) x_a^h$$

$$+ \left[\frac{\partial w_a}{\partial x_a^h} x_a^h + w_a - \rho_a \right] \frac{\partial x_a^h}{\partial \rho_a} \frac{\partial \rho_a}{\partial z_a} \frac{\partial z_a}{\partial r_a} + \left[\frac{\partial w_b}{\partial x_a^f} x_a^f + w_a - \rho_a - t \right] \frac{\partial x_a^f}{\partial \rho_a} \frac{\partial \rho_a}{\partial z_a} \frac{\partial z_a}{\partial r_a}$$

$$+ \left[\frac{\partial w_a}{\partial x_a^h} x_a^h + w_a - \rho_a \right] \frac{\partial x_a^h}{\partial \rho_b} \frac{\partial \rho_b}{\partial z_b} \frac{\partial z_b}{\partial r_a} + \left[\frac{\partial w_b}{\partial x_a^f} x_a^f + w_a - \rho_a - t \right] \frac{\partial x_a^f}{\partial \rho_b} \frac{\partial \rho_b}{\partial z_b} \frac{\partial z_b}{\partial r_a}$$

$$+ \left\{ \left[\frac{\partial w_a}{\partial x_b^f} \frac{\partial x_b^f}{\partial \rho_a} x_a^h + \frac{\partial w_b}{\partial x_b^h} \frac{\partial x_b^h}{\partial \rho_a} x_a^f \right] \frac{\partial \rho_a}{\partial z_a} - [x_a^h + x_a^f] \frac{\partial \rho_a}{\partial z_a} - (1 - \zeta_a) \right\} \frac{\partial z_a}{\partial r_a}$$

$$+ \left[\frac{\partial w_a}{\partial x_a^h} \frac{\partial x_b^f}{\partial \rho_b} x_a^h + \frac{\partial w_b}{\partial x_b^h} \frac{\partial x_b^h}{\partial \rho_b} x_a^f \right] \frac{\partial \rho_b}{\partial z_b} \frac{\partial z_b}{\partial r_a} - \zeta_a \frac{\partial z_a}{\partial r_a} = 0,$$

where we have eliminated $(\frac{\partial w_a}{\partial x_a^h} x_a^h + w_a - \rho_a) \frac{\partial x_a^h}{\partial r_a}$ since this term is equal to zero (see the discussion of 13 above). Firstly, observe that the fifth, sixth, seventh and eighth term in (19) are all zero by (9) and (10). Then, note that ninth term in (19) is zero by (15). Hence, (19) can be written:

⁹Note that we have: $x_a^h = x_a^h(\rho_a(z_a), \rho_b(z_b), r_a)$, $x_b^f = x_b^f(\rho_a(z_a), \rho_b(z_b), r_a)$, $x_b^h = x_b^h(\rho_a(z_a), \rho_b(z_b), r_b)$ and $x_a^f = x_a^f(\rho_a(z_a), \rho_b(z_b), r_b)$.

$$CS' \frac{\partial q_a}{\partial r_a} + \varepsilon \left[q_a - (1 - r_a) \frac{\partial q_a}{\partial r_a} \right] + [CS' - \varepsilon(1 - r_a)] \frac{\partial q_a}{\partial w_a} \frac{\partial w_a}{\partial r_a} + \quad (20)$$

$$\left(\frac{\partial w_a}{\partial r_a} + \frac{\partial w_a}{\partial x_b^f} \frac{\partial x_b^f}{\partial r_a} \right) x_a^h + \left[\frac{\partial w_a}{\partial x_a^h} \frac{\partial x_b^f}{\partial \rho_b} x_a^h + \frac{\partial w_b}{\partial x_b^h} \frac{\partial x_b^h}{\partial \rho_b} x_a^f \right] \frac{\partial \rho_b}{\partial z_b} \frac{\partial z_b}{\partial r_a} - \zeta_a \frac{\partial z_a}{\partial r_a} = 0$$

The first four terms on the left hand side of (20) are the same as in (13), and were discussed above. Then, there is one new strategic effect; a *rival R&D effect*, $\left[\frac{\partial w_a}{\partial x_a^h} \frac{\partial x_b^f}{\partial \rho_b} x_a^h + \frac{\partial w_b}{\partial x_b^h} \frac{\partial x_b^h}{\partial \rho_b} x_a^f \right] \frac{\partial \rho_b}{\partial z_b} \frac{\partial z_b}{\partial r_a}$. Finally, the last term is just the fiscal cost of the R&D subsidy.

The *rival R&D effect* tells us in what direction environmental policy shifts oligopoly profit between the two abatement firms in both markets. If $\frac{\partial z_b}{\partial r_a} > 0$, that is, a stricter climate target in Jurisdiction A induces the upstream firm in Jurisdiction B to do more environmental R&D, profit is actually shifted away from the domestic firm towards the foreign firm by a stricter standard. This happens since the stricter standard will make it possible for the foreign firm to commit to a higher level of environmental R&D (note that the term in brackets is always positive). As discussed above $\frac{\partial z_b}{\partial r_a} > 0$ is likely if the trade barrier is low compared to the constant marginal cost of producing carbon capture equipment. With environmental R&D we thus have to extend Proposition 4 the following proposition:

Proposition 7 *A small, open economy may have incentives to set an especially stringent environmental policy. However, only one of the three mentioned effects pulls unambiguously in this direction:*

1. *A strict emission standard will make carbon abatement cheaper. This is the price effect, which pulls unambiguously in the direction of a more stringent policy.*
2. *A strict emission standard may reduce the abatement industry's ability to extract rents in its domestic market. This is the rent effect, which may pull in the direction of a weaker policy. However, the sign of the rent effect is ambiguous.*
3. *A strict emission standard may shift oligopoly profit away from the domestic abatement industry. This is the rival R&D effect, which may pull in the direction of a weaker policy. However, the sign of the rival R&D effect is ambiguous.*

In the simulations we find that both Point 2 and 3 above pull in the direction of a *less stringent* policy, that is, both the rent effect and the rival R&D effect are negative when policy is set at the textbook rule, i.e., with

marginal abatement costs equal to the quota price. On the other hand, both effects are dominated by the price effect, and in general we find that a stringent policy is desirable.

We have not yet discussed the effect on welfare of a R&D subsidy. The first-order condition for the optimal R&D subsidy is given:

$$\frac{\partial W_a}{\partial \zeta_a} = [CS' - \varepsilon(1 - r_a)] \frac{\partial q_a}{\partial w_a} \frac{\partial w_a}{\partial \zeta_a} + \left[\frac{\partial w_a}{\partial x_a^h} \frac{\partial x_b^f}{\partial \rho_b} x_a^h + \frac{\partial w_b}{\partial x_b^h} \frac{\partial x_b^h}{\partial \rho_b} x_a^f \right] \frac{\partial \rho_b}{\partial z_b} \frac{\partial z_b}{\partial \zeta_a} - \zeta_a \frac{\partial z_a}{\partial \zeta_a} = 0. \quad (21)$$

We assume that $\frac{\partial^2 W_a}{\partial (\zeta_a)^2} < 0$, and hence, that a maximum exists. The first term is the price effect again. Since a subsidy to R&D lowers the price on carbon capture, the output of electricity and consumer surplus increases. As shown above, for $r_a \geq r_a^0$, the price effect $[CS' - \varepsilon(1 - r_a)] \frac{\partial q_a}{\partial w_a} \frac{\partial w_a}{\partial \zeta_a}$ must be positive.

The next term is the strategic effect, which is positive, since the term $\frac{\partial z_b}{\partial \zeta_a}$ is negative. That is, an R&D subsidy leads to lower levels of R&D spending abroad, and this benefits the domestic firm through increased market share both at home and abroad. This implies the following proposition:

Proposition 8 *For the first best or a stringent environmental policy i.e. $r_a \geq r_a^0$, we have $\zeta_a > 0$. That is, the government should provide an R&D subsidy.*

Hence, the use of a stringent environmental policy does not rule out the use of an environmental R&D subsidy and vice-versa. In the numerical simulations the optimal R&D subsidy is small, and becomes higher/smaller if the proportional standard is strengthened/weakened.

6 Numerical simulations

In order to shed light on the theoretical analyses, we will present the results of some numerical simulations. Some of the theoretical conclusions are ambiguous, and even when the sign of direction is unambiguous, it may be interesting to look into the size of these effects within a realistic framework. We will apply a numerical representation of the model described above, presented in Greaker and Rosendahl[8].

6.1 Brief model description

The model describes the competition between one firm in a small Country A and n symmetric firms in a large Region B. All firms supply carbon capture equipment to both countries/regions, after doing R&D in a preceding stage. In deciding upon the amount of R&D we assume that the n firms in Region B form an R&D joint venture. That is, they decide cooperatively upon the amount of R&D, and benefit equally from the results.¹⁰

¹⁰This distinction between cooperation in the R&D stage and competition in the output market has been analyzed theoretically by D'Aspremont and Jacquemin[1] and Kamien et

The three functions that are not fully specified in the theoretical sections above are the demand function $q_i(p_i)$, the emission function $e_i(q_i, x_i)$ and the R&D function $\rho(z_i)$. In the simulation model, a linear demand function is chosen. Moreover, the following emission function is used, which satisfies the properties assumed in Section 2:¹¹

$$e_i = \frac{q_i}{1 + \frac{x_i}{q_i}}. \quad (22)$$

The R&D function is assumed to have the same shape as the well-known learning curve, i.e., that the marginal costs of the technology fall by a fixed percentage rate for every doubling of accumulated input z_i . Although learning curves have mainly been used to estimate the relationship between unit costs and accumulated use or investment of a technology (i.e., learning by doing), Klaassen et al.[12] estimate successfully a two-factor learning curve for wind power where R&D expenditures are included in addition to cumulative capacity. Moreover, according to Gielen and Podkanski[7] learning by R&D will be more important for the future costs of CCS than LBD, as opposed to costs of renewables (see also OECD[15], p. 78). Thus, we specify the following function:

$$\rho(z_i) = \bar{\rho}_i(z_i + z_{i,0})^{\sigma_i} \quad (23)$$

where z_0 denotes historic accumulated R&D input, i.e., before the game starts. The rest of the extended model is presented in a the companion paper [8].

The numerical model is calibrated to fit two separate electricity markets, and the supply of carbon capture technology as the only mean to reduce CO_2 emissions. The electricity markets are similar in all respects but the size of the market (the large region B being about 20 times larger than the small country A). The main parameter values are shown in Table A1 in Appendix D, and are described more fully in Greaker and Rosendahl[8].

Here we will briefly mention some of the most important parameter values. The unit costs of the carbon capture technology amount to 35-40 per cent of the electricity costs. In addition comes costs of transport and storage, which amount to about 10 per cent of the electricity costs, but are fixed over time. The learning rate for the R&D activity is assumed to be 13 per cent. The international quota price on CO_2 emissions in stage 3 is set to 10 Euro per MWh (i.e., 25 Euro per ton CO_2 for an average gas power plant), and the number of firms in Region B is set to four. Note that the findings below

al.[11]. The latter paper concludes that a research joint venture yields the highest consumer and producer surplus, as duplication of R&D activities is avoided and product prices are not as high as with monopoly. Moreover, with external trade it is reasonable to assume that the firms in Region B will benefit from cooperating in the R&D stage, but not in the output market, as the latter would imply more aggressive behavior from foreign firms, see for example Salant et al.[20].

¹¹By solving for the emission function (22) we have $x_i(r_i) = \frac{r_i}{1-r_i}$.

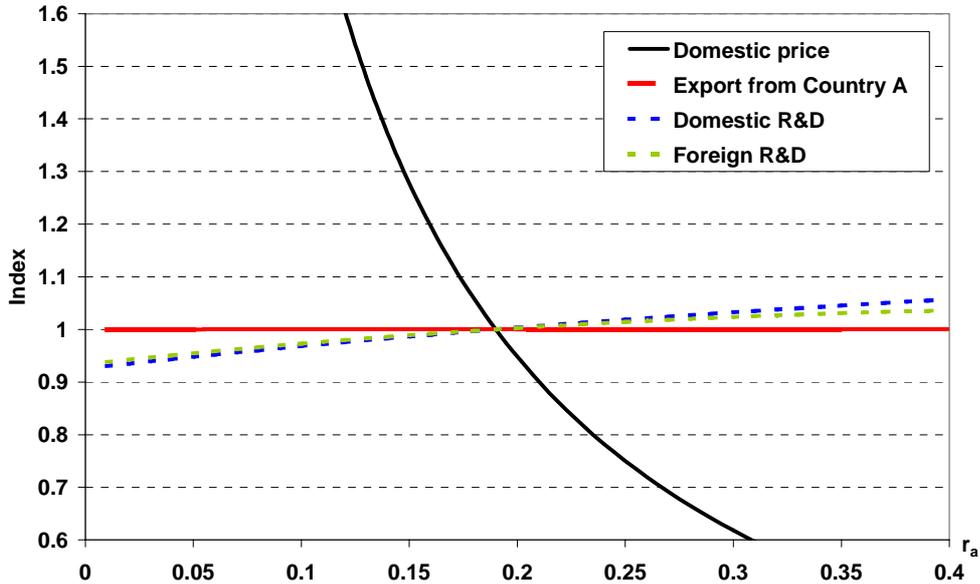
seem to be very robust to alternative specifications of parameters such as the number of firms, technology costs and learning potential.

When it comes to policy in Region B, we assume that it is fixed and unaffected by policy etc. in Country A. This is reasonable inasmuch as the optimal policy in Region B is approximately insensitive to the policy of the small country A. More specifically, we assume that the emission standard in Region B is set equal to $r_B = 0.1$. We also assume that there is no R&D support in that region.

6.2 The effects of tighter environmental standard

Before examining the optimal combination of policy in Country A, let us look at the effects of tightening the environmental standard in the small country. Figure 1 shows how different levels of the standard affect the domestic price of the capture technology, export of this technology to the large region, and R&D efforts in both countries/regions. The results are presented as indexes (I), with $I = 1$ when the standard is set at its optimal level (see below). The R&D subsidy is fixed in Figure 1, and set to its optimal level.

Figure 1. Effects of different emission standards in Country A on selected variables. Index ($I = 1$ at $r_a = r_a^*$)



From Proposition 3 above we know that the price of the technology falls when the standard increases. In Figure 1 we see that this price effect is very significant. The price is approximately halved when the emission standard is doubled.

R&D efforts in both countries/regions are somewhat increased when the standard is raised - domestic research increases slightly more in relative terms than foreign research. In the theoretical analyses above we were not able to

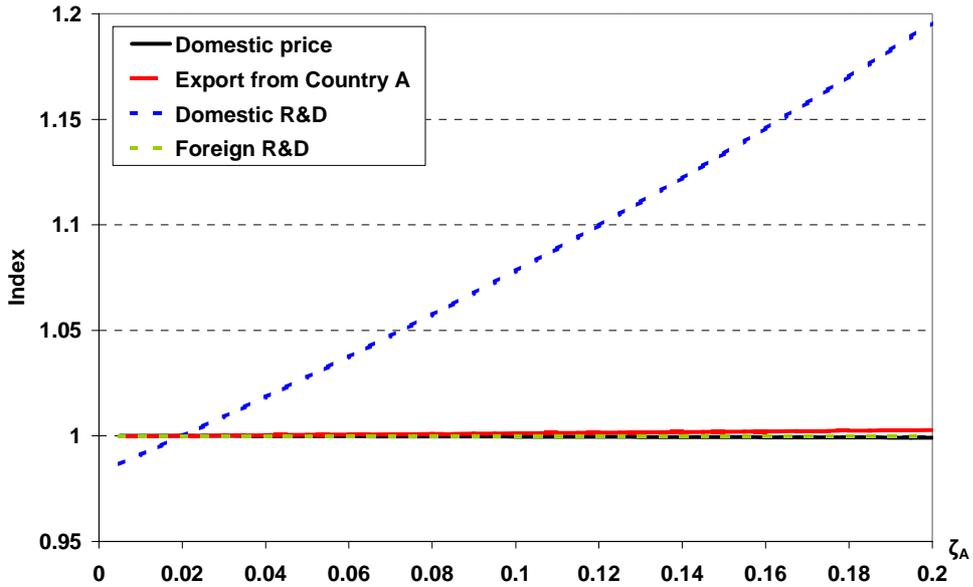
sign the effect on R&D in general, but argued that it would be reasonable to assume a positive association between emission standard and R&D efforts, particularly with low trade costs. The numerical simulations at least confirm this assumption.

Finally, the technology export increases by only 0.1 per cent when the standard is increased from 0.01 to 0.4, which reflects that the standard in general has an ambiguous effect on export (see Proposition 6).

6.3 The effects of higher R&D subsidies

Let us now take a look at the effects of higher subsidy rates on R&D in Country A. Figure 2 shows the effects of different subsidy rates on the same variables as in Figure 1. In Figure 2 the indexes are set to $I = 1$ when the subsidy rate is set at its optimal level (see below). Now the standard is fixed and set to its optimal level.

Figure 2. Effects of different R&D subsidy rates in Country A on selected variables. Index ($I = 1$ at $\zeta_a = \zeta_a^*$)



According to Proposition 5 the domestic price of the technology falls when the R&D subsidy is raised. This is also the case in Figure 2, but the price decrease is really insignificant (0.1 per cent). This is striking compared to the price decrease in Figure 1. Thus, the numerical simulations definitely show that the emission standard is much more able to push down the technology price and consequently the abatement costs.

On the other hand, the R&D subsidy naturally has a stronger impact on the domestic R&D effort, whereas R&D effort in the large region falls. The signs of both these effects were found to hold in general (see Table I above). The impact on foreign R&D is however almost zero, which is partly (but not only) due the differences in size of Country A and Region B.

Proposition 6 stated that technology export would unambiguously rise

when the R&D subsidy was raised. Figure 2 shows, however, that this effect also is very small (0.3 per cent).

To sum up so far, the numerical simulations clearly indicate that the emission standard is the most powerful policy tool when it comes to bringing domestic abatement costs down. Furthermore, none of these policy tools seem to have any significant bearing on the export potential of the technology, at least within our chosen modelling framework. These observations are useful when we now turn our eyes on the optimal combination of policy in Country A.

6.4 Optimal combination of policy in Country A

The simple textbook rule says that the optimal R&D subsidy (ζ_a^*) is zero as there are no spillover effects, and that the optimal emission standard (r_a^*) should be set so that marginal abatement cost equals the international quota price (i.e., $r_a^* = r_a^0$). However, as we have seen in the theoretical part of the paper, the imperfect market situation will generally lead to other conclusions. We showed theoretically that the R&D subsidy should be positive, whereas the emission standard could be either higher or lower than r_a^0 (i.e., $r_a^* \leq r_a^0$).

On the other hand, we noted above that the emission standard seemed to have very significant effects on the domestic market, whereas the R&D subsidy seemed to have only minor effects on both technology price and export.

Figure 3. Welfare in Country A with different combinations of emission standard and R&D subsidy

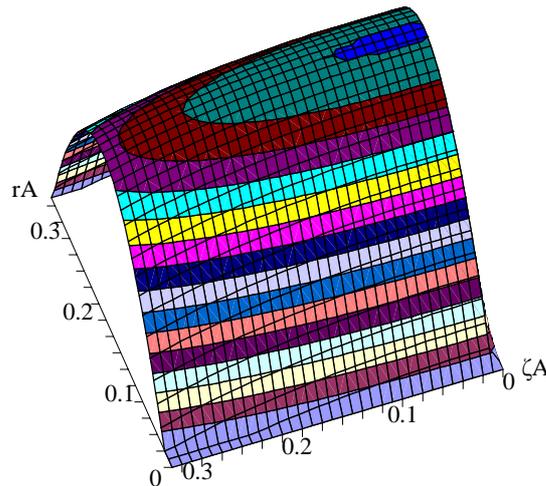


Figure 3 shows how the welfare of Country A (displayed as indifference curves) is affected by various combinations of these two policy instruments. The optimal combination is an emission standard of $r_a^* = 0.19$ and an R&D

subsidy of $\zeta_a^* = 0.04$. At this standard the direct marginal abatement costs are about 2 times higher than the international quota price. This reflects that the price effect discussed in Proposition 7 clearly dominates the rent effect and the rival R&D effect. When looking at Figure 1, this comes at no surprise.

In fact, for any positive r_a the direct marginal abatement costs exceed the international quota price, so that $r_a^0 = 0$. The marginal abatement costs are actually *falling* in r_a up to about $r_a = 0.25$. The reason is that the drop in technology price from higher standard dominates the increased marginal costs for a given price.

As demonstrated theoretically above, the R&D subsidy should be positive even in the absence of spillover effects. First, it contributes to lower market price of the technology due to lower costs and thus more aggressive behavior of the domestic firm. Second, the R&D subsidy has a positive strategic effect. Nevertheless, the size of the optimal R&D subsidy is quite small, which reflects that the positive effects of the subsidy are very small after all (cf. Figure 2 discussed above). Thus, with no spillover effects massive support of domestic research is not recommended.

If we look closer at Figure 3, we note that the optimal choice of emission standard is completely independent of the choice of R&D subsidy. Although a higher subsidy rate stimulates domestic R&D (cf. Figure 2), the technology price is only marginally decreased, and so are the costs of abatement. On the other hand, the optimal R&D subsidy is quite dependent on the choice of emission standard. This complementarity follows from the fact that when a strong standard is imposed, more abatement technology is needed, and the benefits of more R&D increase. The figure also shows quite clearly that choosing the right emission standard is much more important than picking the optimal R&D subsidy.

7 Discussion

How robust are the conclusions drawn above? One way of testing this is to run a number of simulations, with different combinations of the uncertain parameters. By running several hundred simulations, varying the most important parameters in the model, we find that the observations in Figure 1 and 2 are indeed very robust. The price effect of changing the standard is very significant, the technology export is insensitive to the standard and also reacts little to the subsidy, whereas both policy tools stimulate R&D efforts (subsidies clearly most). As the results are not very dependent on the parameter values, we dare say that the qualitative results may be generalized to other small countries facing similar environmental and technology challenges, and market conditions.

The optimal combination of policy is of course more sensitive to the parameter choices. Nevertheless, the optimal subsidy rate is generally small (below 0.1). More interestingly, at the optimal standard the direct marginal abatement costs generally exceed the international quota price.¹²

¹²There is one exception to this conclusion. Due to our choice of linear demand function,

A more critical objection against our analyses is our choice of modelling, and in particular our choice of policy instrument, i.e., the emission standard. As mentioned in Section 2, our implementation of a standard is very similar to green certificate markets, as implemented or proposed for the electricity market in several countries (e.g., Norway and Sweden) and discussed in others (e.g., the EU). A proportional standard could also be implemented within a quota market, if firms receive free allowances for a certain level of emissions per produced output. This is actually the case for new entrants in the Emission Trading Scheme in the EU (and Norway), and could possibly become extended to incumbents from 2013. Today, however, there is very little credit for carbon capture and storage in the EU ETS, as the power plant risk not receiving any free emission allowances, and there is no credit at all in current green certificate markets. Thus, it is not obvious how CCS will be rewarded in future environmental policies.

Nevertheless, it is important to draw attention to some particularities with the effects of the emission standard. One is the impact on producer surplus. As the emission standard implies that some purchase of the technology is always necessary, no matter what the price is, the price of the technology (i.e., the mark up) is very sensitive to the size of the standard. This actually implies that the producer surplus generally *falls*, though not much, when the standard increases. The price effect is more important than the output effect.

To test how sensitive the conclusions are to the choice of environmental policy, we have also done analyses with an emission ceiling (e.g., implemented by a domestic quota market) instead of an emission standard. In order to obtain explicit first order conditions, we had to change our emission function to a simpler one (i.e., $e_i = q_i/x_i$). In this case all the theoretical findings carry over completely. Moreover, the findings in Figure 1 and 2 are completely reproduced. In particular, the price of the technology falls significantly when the emission quota is reduced, whereas the export level is approximately unchanged. The effects of higher R&D subsidies are almost identical to the results in Figure 2.

8 Conclusion

Implementing an especially stringent climate policy may be well founded, even for a small country. That is, a small country may benefit from setting emission reduction targets implying that marginal abatement costs exceed the international quota price. Such a policy will increase domestic competition between carbon abatement suppliers, and lead to lower carbon abatement costs.

the marginal abatement costs have an upper limit. Thus, if the international quota price exceeds this limit, any level of r_a means that marginal abatement costs are below the quota price. Still, the optimal level of r_a will typically be very high, but not equal to one. In this case the price effect will be negative, as the emission price effect will dominate the consumer surplus effect of increased output. As we believe the linear demand assumption to be reasonable only at normal levels of production, our focus lies on the results with moderate levels of standard.

On the other hand, an especially stringent environmental policy is not a particularly good industrial policy as long as the purpose is to develop new successful export sectors. Although a stronger environmental policy will lead to more domestic environmental research, also foreign firms will increase their R&D spending and their sales of abatement technology to the small country.

In order to deal with the Kyoto Protocol, both the EU and Norway have recently initiated an emission trading scheme (ETS), covering the power sector and some major industry sectors. However, as emission allowances are allocated freely to the emitting firms, the ETS gives little incentives to install carbon capture technologies (or invest in renewable energy), as valuable allowances then would be lost. This could be altered if the allocation of allowances were based on *energy production*, and not *emissions*, including CCS and other CO_2 -free energy production.

In light of this lack of technology incentives, subsidy programs to carbon abatement technologies could be seen as a compensation, leading the way towards future abatement of carbon emissions. Somewhat to our surprise, the results in this paper do not support this activist policy, but rather the contrary. The explanation is that supporting research on clean technologies makes little sense if it is not backed up by clear incentives in the market to implement the clean technology.

So far, we must therefore conclude that the case for extensive subsidizing of carbon abatement firms is clearly rather weak. Remember that an R&D subsidy has two favorable effects within our model concept: 1) it lowers the domestic abatement price, and 2) it shifts profit from the foreign firms to the domestic firm. With respect to the latter effect, we find that the strategic effect of a subsidy is small. This is the case even though we model the carbon abatement market with Cournot competition and without free entry of new firms, leading to large profits in the domestic carbon abatement firm. Bertrand competition with differentiated carbon abatement technologies, or free entry of new firms, would presumably yield an even smaller strategic motive for an R&D subsidy. With respect to the first effect, our results suggest that a stringent standard is far more effective in lowering the domestic carbon abatement cost.

Clearly, a possible third favorable effect of an R&D subsidy could arise if there were *domestic* spillover effects within the small country (see e.g. Lund[13]). In our analyses we have not considered this possibility, as we have assumed only one domestic firm in Country A. Future research should look more into this question, as well as examining the effects of alternative policy instruments such as deployment subsidies and emission taxes or quotas. Nevertheless, our findings suggest that the main focus should be on implementing a sufficiently stringent climate policy, and, in particular, not replace it with an extensive subsidy programs.

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A The supply of carbon capture technology

As mentioned, we assume $\frac{dx_i}{dr_i} > 0$. The sufficient conditions are:

$$2p'_a + \frac{x_a^h + x_b^f}{x_a(r_a)} p''_a < 0, \quad (24)$$

$$p_a - c_0 + \frac{x_a^h + x_b^f}{x_a(r_a)} p'_a \leq 0, \quad (25)$$

where the latter conditions holds as long as $\left| \frac{x_b^f}{x_a(r_a)} p'_a \right| \geq v_a + \rho_a$.

The two markets for carbon capture technology have identical structures, and are both independent of the climate policy in the other jurisdiction. Hence, it should be enough to look at one of the markets when determining the effect of climate policy on supply of carbon capture technology. Inserting according to: $w_i(x_i, r_i) = \frac{1}{x_i(r_i)} p_i \left(\frac{x_i}{x_i(r_i)} \right) - \frac{c_0}{x_i(r_i)} - v_i$, we have for the two first-order conditions (Country A):

$$\begin{aligned} \frac{\partial \pi_a}{\partial x_a^h} &= \frac{x_a^h}{[x_a(r_a)]^2} p'_a + \frac{1}{x_a(r_a)} p_a - \frac{c_0}{x_a(r_a)} - v_a - \rho_a = 0 \\ \frac{\partial \pi_b}{\partial x_b^f} &= \frac{x_b^f}{[x_a(r_a)]^2} p'_a + \frac{1}{x_a(r_a)} p_a - \frac{c_0}{x_a(r_a)} - v_a - \rho_b - t = 0 \end{aligned} \quad (26)$$

The second-order conditions are $\frac{1}{[x_a(r_a)]^2} \left[2p'_a + \frac{x_a^h}{x_a(r_a)} p''_a \right]$ and $\frac{1}{[x_a(r_a)]^2} \left[2p'_a + \frac{x_b^f}{x_a(r_a)} p''_a \right]$.

We have assumed $\frac{\partial^2 \pi_a}{\partial (x_a^h)^2}, \frac{\partial^2 \pi_b}{\partial (x_b^f)^2} < 0$, which is ensured by (24).

The cross derivatives $\frac{\partial^2 \pi_a}{\partial x_b^f \partial x_a^h}$ and $\frac{\partial^2 \pi_b}{\partial x_a^h \partial x_b^f}$ are $\frac{1}{[x_a(r_a)]^2} \left[p'_a + \frac{x_a^h}{x_a(r_a)} p''_a \right]$ and $\frac{1}{[x_a(r_a)]^2} \left[p'_a + \frac{x_b^f}{x_a(r_a)} p''_a \right]$, respectively. In order to ensure that the strategic variables are substitutes we assume that they are negative as well.

Denote the derivatives above for short $\pi_{aa}, \pi_{bb}, \pi_{ab}$ and π_{ba} , respectively, and assume $\pi_{aa}\pi_{bb} - \pi_{ab}\pi_{ba} > 0$ (in order to ensure a unique equilibrium). For the derivatives $\pi_{ar_a} = \frac{\partial^2 \pi_a}{\partial r_a \partial x_a^h}$ and $\pi_{br_a} = \frac{\partial^2 \pi_b}{\partial r_a \partial x_b^f}$ we have:

$$\pi_{ar_a} = \frac{-x'_a}{[x_a(r_a)]^2} \left[\frac{x_a^h}{x_a(r_a)} (2p'_a + q_a p''_a) + p_a - c_0 + q_a p'_a \right] > 0, \quad (27)$$

where the term outside the brackets is negative. The terms inside the brackets must be negative as well by (24) and (25). This also holds for π_{br_a} :

$$\pi_{br_a} = \frac{-x'_a}{[x_a(r_a)]^2} \left[\frac{x_b^f}{x_a(r_a)} (2p'_a + q_a p''_a) + p_a - c_0 + q_a p'_a \right] > 0. \quad (28)$$

Note that the two expressions in (27) and (28) are identical apart from x_a^h and x_b^f . Hence, as long as $x_b^f < x_a^h$, we have $\pi_{ar_a} > \pi_{br_a}$.

By totally differentiating the two equations in (26) we get:

$$\frac{dx_a^h}{dr_a} = \frac{\pi_{ab}\pi_{br_a} - \pi_{bb}\pi_{ar_a}}{\pi_{aa}\pi_{bb} - \pi_{ab}\pi_{ba}},$$

$$\frac{dx_b^f}{dr_a} = \frac{\pi_{ba}\pi_{ar_a} - \pi_{aa}\pi_{br_a}}{\pi_{aa}\pi_{bb} - \pi_{ab}\pi_{ba}},$$

We then have the following two alternatives:

$$I) \pi_{ba}\pi_{ar_a} - \pi_{aa}\pi_{br_a} < 0 \rightarrow \frac{dx_a^h}{dr_a} > 0 \frac{dx_b^f}{dr_a} < 0$$

$$II) \pi_{ba}\pi_{ar_a} - \pi_{aa}\pi_{br_a} > 0 \rightarrow \frac{dx_a^h}{dr_a} > 0 \frac{dx_b^f}{dr_a} > 0$$

Assume $p_a'' = 0$ and $p_a - c_0 + \frac{x_a^h + x_b^f}{x_a(r_a)} p_a' = 0$. We then have alternative I) if:

$$x_a^h - 2x_b^f > 0$$

In case $\rho_a \lesssim \rho_b + t$, we must have $x_a^h \gtrsim x_b^f$ and alternative II) above. Hence, alternative II) above is the most likely case. In case $\rho_a \ll \rho_b + t$, we have $x_a^h \gg x_b^f$, and alternative I) above may be the case.

Since $\pi_{ar_a} > \pi_{br_a}$, it also follows that $\frac{dx_a^h}{dr_a} \geq \frac{dx_b^f}{dr_a}$.

B The R&D game

B.1 The effect of policy on abatement with R&D

The two first-order conditions from the R&D game can be written:

$$\frac{\partial \omega_i}{\partial z_i} = \left[\frac{\partial \omega_i}{\partial x_{-i}^f} \frac{\partial x_{-i}^f}{\partial \rho_i} x_i^h + \frac{\partial \omega_i}{\partial x_{-i}^h} \frac{\partial x_{-i}^h}{\partial \rho_i} x_i^f \right] \frac{\partial \rho_i}{\partial z_i} - [x_i^h + x_i^f] \frac{\partial \rho_i}{\partial z_i} - (1 - \zeta_i) = 0.$$

In order to ensure an internal maximum we assume $\omega_{ii} < 0$ for $i = a, b$. Further, we assume that the levels of R&D are strategic substitutes i.e. $\omega_{-ii} < 0$ for $i = a, b$. Finally, we assume that the uniqueness condition holds: $\omega_{ii}\omega_{-i-i} - \omega_{-ii}\omega_{i-i} > 0$ for $i = a, b$.

Let ϕ_i denote the exogenous variables r_i , ζ_i and t . Further, denote $\frac{\partial^2 \omega_i}{\partial \phi_i \partial z_i} = \omega_{i\phi}$. Then, by total differentiation we have:

$$\frac{dz_a}{d\phi_i} = \frac{\omega_{ab}\omega_{b\phi} - \omega_{bb}\omega_{a\phi}}{\omega_{aa}\omega_{bb} - \omega_{ab}\omega_{ba}},$$

$$\frac{dz_b}{d\phi_i} = \frac{\omega_{ba}\omega_{a\phi} - \omega_{aa}\omega_{b\phi}}{\omega_{aa}\omega_{bb} - \omega_{ab}\omega_{ba}}.$$

Since $\omega_{aa}\omega_{bb} - \omega_{ab}\omega_{ba} > 0$, we have: $sign \left[\frac{dz_a}{d\phi_i} \right] = sign [\omega_{ab}\omega_{b\phi} - \omega_{bb}\omega_{a\phi}]$ and $sign \left[\frac{dz_b}{d\phi_i} \right] = sign [\omega_{ba}\omega_{a\phi} - \omega_{aa}\omega_{b\phi}]$.

For the derivatives $\omega_{a\zeta_a}$ and $\omega_{b\zeta_a}$ we have:

$$\omega_{a\zeta_a} = 1 \text{ and } \omega_{b\zeta_a} = 0, \quad (29)$$

We then get for the levels of R&D:

$$\text{sign} \left[\frac{dz_a}{d\zeta_a} \right] = \text{sign} [-\omega_{bb}] \text{ and } \text{sign} \left[\frac{dz_b}{d\zeta_a} \right] = \text{sign} [\omega_{ab}].$$

Both signs are unambiguous, and given directly from the assumption about the signs on the derivatives. For the two other cross-derivatives we have:

$$\omega_{ar_a} = \left[\frac{\partial^2 \omega_a}{\partial r_a \partial x_b^f} \frac{\partial x_b^f}{\partial \rho_a} x_a^h + \frac{\partial \omega_a}{\partial x_b^f} \frac{\partial^2 x_b^f}{\partial r_a \partial \rho_a} x_a^h + \frac{\partial \omega_a}{\partial x_b^f} \frac{\partial x_b^f}{\partial \rho_a} \frac{\partial x_a^h}{\partial r_a} - \frac{\partial x_a^h}{\partial r_a} \right] \rho'(z_a) > 0, \quad (30)$$

$$\omega_{br_a} = \left[\frac{\partial^2 \omega_a}{\partial r_a \partial x_a^h} \frac{\partial x_a^h}{\partial \rho_b} x_b^f + \frac{\partial \omega_a}{\partial x_a^h} \frac{\partial^2 x_a^h}{\partial r_a \partial \rho_b} x_b^f + \frac{\partial \omega_a}{\partial x_a^h} \frac{\partial x_a^h}{\partial \rho_b} \frac{\partial x_b^f}{\partial r_a} - \frac{\partial x_b^f}{\partial r_a} \right] \rho'(z_b) \begin{matrix} \geq \\ \leq \end{matrix} 0, \quad (31)$$

where we assume based on Lemma 1 that $\frac{\partial^2 \omega_a}{\partial r_a \partial x_b^f}, \frac{\partial^2 \omega_a}{\partial r_a \partial x_a^h} < 0$, and based on the upstream market becoming larger that $\frac{\partial^2 x_b^f}{\partial r_a \partial \rho_a}, \frac{\partial^2 x_a^h}{\partial r_a \partial \rho_b} > 0$. Further, if $\frac{\partial x_b^f}{\partial r_a} > 0$, we also have $\omega_{br_a} > 0$.

For $z_a = z_b$ and $t > 0$, we have $\frac{dz_a}{dr_a} > 0$, since in a symmetric equilibrium $|\omega_{ab}| < |\omega_{bb}|$ and $\frac{\partial x_b^f}{\partial r_a} < \frac{\partial x_a^h}{\partial r_a}$. It seems reasonable to assume that $\frac{dz_a}{dr_a} > 0$ also when $z_a \neq z_b$. This is also confirmed by our numerical simulations.

The derivative $\frac{dz_b}{dr_a}$ cannot be signed. If $\frac{\partial x_b^f}{\partial r_a} < 0$, and the two last terms in (31) dominate the two first terms such that $\omega_{br_a} < 0$, we have $\frac{dz_b}{dr_a} < 0$. On the other hand, for $z_a = z_b$ and $t = 0$, we must have $\frac{dz_b}{dr_a} > 0$, since for $t = 0$; $\frac{\partial x_b^f}{\partial r_a} = \frac{\partial x_a^h}{\partial r_a}$.

C The effect of policy on the abatement price

We assume in line with general Cournot theory that $\frac{\partial w_i}{\partial \rho_i}, \frac{\partial w_i}{\partial \rho_{-i}} > 0$, i.e. that the Nash-equilibrium price increases if one of the two firms experiences an increase in marginal production costs.

We then have:

$$\frac{dw_i}{dr_i} = \frac{\partial w_i}{\partial r_i} + \frac{\partial w_i}{\partial \rho_i} \frac{\partial \rho_i}{\partial z_i} \frac{\partial z_i}{\partial r_i} + \frac{\partial w_i}{\partial \rho_{-i}} \frac{\partial \rho_{-i}}{\partial z_{-i}} \frac{\partial z_{-i}}{\partial r_i} < 0,$$

since $\frac{\partial w_i}{\partial r_i} < 0$ and $\frac{\partial w_i}{\partial \rho_i} > 0$, $\frac{\partial \rho_i}{\partial z_i} \frac{\partial z_i}{\partial r_i} < 0$ and $\left| \frac{\partial \rho_i}{\partial z_i} \frac{\partial z_i}{\partial r_i} \right| \geq \left| \frac{\partial \rho_{-i}}{\partial z_{-i}} \frac{\partial z_{-i}}{\partial r_i} \right|$.

The effect of the R&D subsidy on the price of carbon capture is given:

$$\frac{\partial w_i}{\partial \zeta_i} = \frac{\partial w_i}{\partial \rho_i} \frac{\partial \rho_i}{\partial z_i} \frac{\partial z_i}{\partial \zeta_i} + \frac{\partial w_i}{\partial \rho_{-i}} \frac{\partial \rho_{-i}}{\partial z_{-i}} \frac{\partial z_{-i}}{\partial \zeta_i} < 0,$$

since $\frac{\partial \rho_i}{\partial z_i} \frac{\partial z_i}{\partial \zeta_i} < 0$ and $\left| \frac{\partial \rho_i}{\partial z_i} \frac{\partial z_i}{\partial \zeta_i} \right| \geq \left| \frac{\partial \rho_{-i}}{\partial z_{-i}} \frac{\partial z_{-i}}{\partial \zeta_i} \right|$.

D Parameter values in numerical model

Table A1. Main parameter values in the numerical model

| Parameter | | Country A | Region B |
|-------------------------------------|----------------|--------------|--------------|
| Unit cost electricity | c_i | 25 Euro/MWh | 25 Euro/MWh |
| Choke price electricity | S_i | 62 Euro/MWh | 62 Euro/MWh |
| Slope in demand function | s_i | 0.01 | 0.0005 |
| R&D learning exponent | σ_i | -0.2 | -0.2 |
| R&D parameter | $\bar{\rho}_i$ | 19 | 19 |
| Initial (accumulated) R&D effort | $z_{i,0}$ | 32 M Euro | 32 M Euro |
| Unit storage cost | v_i | 2.4 Euro/MWh | 2.4 Euro/MWh |
| Unit trade cost for abatement tech. | t | | 2 Euro |
| Number of firms | n_i | 1 | 4 |
| International quota price | ϵ | | 10 Euro/MWh |
| Discount rate | | | 7% |
| Length of stage 2 (R&D stage) | $\Delta\tau$ | | 10 years |
| Length of stage 3 (Cournot stage) | | | 20 years |

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