Working Paper 12/2012

Emissions leakage and subsidies for pollution abatement

Pay the polluter or the supplier of the remedy?

Carolyn Fischer, Mads Greaker and
Knut Einar Rosendahl

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-125-4
ISSN: 1892-9680
http://cree.uio.no

Carolyn Fischer, Mads Greaker and
Knut Einar Rosendahl

Emissions leakage and subsidies for pollution abatement

Pay the polluter or the supplier of the remedy?

Abstract:
Asymmetric regulation of a global pollutant between countries can alter the competitiveness of industries and lead to emissions leakage. For most types of pollution, abatement technologies are available for firms to produce with lower emissions. However, the suppliers of those technologies tend to be less than perfectly competitive, particularly when both emissions regulations and advanced technologies are new. In this context of twin market failures, we consider the relative effects and desirability of subsidies for abatement technology. We find a more robust recommendation for upstream subsidies than for downstream subsidies. Downstream subsidies tend to increase global abatement technology prices, reduce pollution abatement abroad and increase emission leakage. On the contrary, upstream subsidies reduce abatement technology prices, and hence also emissions leakage.

Keywords: Emissions leakage; Abatement subsidies; Upstream technology market

JEL classification: Q54; H23; L13

Acknowledgements: We are grateful to Cathrine Hagem for comments on an earlier draft, and for financial support from the Research Council of Norway (through the Renergi programme and CREE), and from Entwined-Mistra.

Address: Mads Greaker, Statistics Norway, Research Department. E-mail: mgr@ssb.no
Knut Einar Rosendahl, Statistics Norway, Research Department. E-mail: ker@ssb.no
Carolyn Fischer, Resources for the Future. E-mail: fischer@rff.org

1 Introduction

Our point of departure is asymmetric environmental regulation of a global pollutant. One example is greenhouse gas (GHG) emissions and the Kyoto protocol, which divides countries into Annex B and Non-Annex B countries. The asymmetry in regulation between countries may alter the competitiveness of industries and lead to *emissions leakage*. Emissions leakage occurs whenever efforts by one country to reduce emissions lead to increased emissions in other countries. The welfare costs of meeting targets of environmental protection are then increased both globally and in the country with a more stringent environmental policy.

In the case of a global pollutant, marginal abatement costs should ideally be equalized across countries. There are several reasons why this rule may not be implemented. For GHGs, the United Nations Framework Convention on Climate Change (UNFCCC) explicitly states that countries have common but differentiated responsibilities. At the meeting among the parties to the UNFCCC in Copenhagen in December 2009, countries agreed to set GHG mitigation targets, but targets were to be voluntary, and the stringency of the targets will not be harmonized. Differentiated responsibilities between developed and developing countries is also a part of the Montreal Protocol on substances that deplete the ozone layer.

In this paper we assume that it is not politically possible for governments to equalize environmental policy between regions. The difference in costs induced by the asymmetric environmental regulation of industries will then lead to emissions leakage. From the literature it is well known that emissions leakage can be partly counteracted by trade policy e.g. a combination of tariffs and export subsidies (Hoel 1996; Mæstad 1998,2001; Böhringer et al. 2010). However, it remains unclear whether attempts to regulate production processes in other countries (such as with embodied carbon tariffs) would be found in accordance with WTO rules; see for instance Greaker (2006) or Fischer and Fox (2012).

According to the WTO, supporting the deployment and diffusion of green technologies is not hindered by WTO rules (WTO 2011). For most types of pollution, abatement technologies exist that make it possible for firms to produce with fewer emissions. According to recent studies, cited in among others Requate (2005) and David and Sinclair-Desgagné (2010), the supply of abatement technology takes place in separate abatement technology firms. Our research question is therefore not only whether abatement subsidies should be used to limit emissions leakage , but also whether abatement subsidies should be given upstream or downstream. That is, should you pay the polluters to use pollution abatement equipment, or should you pay the pollution abatement equipement firms to increase their supply?

Current policy seems to favor paying the polluters. One example is the French tax on air pollution, where tax revenues are used to support investment in abatement technologies, particularly in industrial sectors (Millock and Nauges, 2006). The same happens in Norway in which the government has established separate public funds financing both NOx and GHG abatement technology investment in industries. Finally, cap-and-trade with output-based allocation of quotas, which will be the dominant allocation mechanism in the EU Emissions Trading System from 2013, is also a subsidy to polluting firms, and will indirectly boost domestic investments in low-carbon technologies.

Our findings suggest that upstream subsidies are a more robust reccomandation than downstream subsidies. Downstream subsidies stimulate demand for abatement technologies, leading to higher international prices of such technologies. This tends to reduce pollution abatement abroad and increase emissions leakage. From a regional perspective, downstream subsidies may weaken the position of the domestic abatement technology firms and shift profits abroad. On the contrary, upstream subsidies stimulate supply of abatement technologies, leading to lower technology prices and hence also less emissions leakage. Furthermore, from the perspective of the home region, they shift rents home, as they provide domestic abatement technology firms with a competitive advantage.

The result that upstream subsidies improve the environmental performance of foreign industries, hence limiting leakage, has some resemblance to Golombek and Hoel (2004). They found that R&D investments in industrialized countries may reduce emissions in developing countries if there are technology spillovers that reduce developing countries' abatement costs. We find the same effect without assuming R&D spillovers. Simply supporting the upstream abatement technology firm in one country will, through international trade in abatement technology, reduce the emissions intensity in other countries.

Our model has many similarities with Greaker and Rosendahl (2008). They found that it could be optimal for a single country to impose an excessively stringent environmental policy in order to reduce the mark-up of technology suppliers, and hence increase the diffusion of these technologies. In this study the upstream subsidy plays a similar role. Strategic effects with regards to the competition between domestic and foreign upstream suppliers were less important in Greaker and Rosendahl (2008). From a home region perspective that could however constitute an important aspect of an upstream support policy.

As mentioned, there are many studies of the use of trade measures to counteract emissions leakage. In addition to this strand of literature, Demailly and Quirion (2012) look at emissions permit allocation schemes as a measure to limit emissions leakage. In a numerical simulation of the European cement industry under the European emissions trading system (ETS), they find that output-based allocation of emissions permits may significantly limit leakage, as opposed to grandfathering (lump-sum allocations). Output based allocation will also likely boost the demand for abatement equipment, and hence may imply higher prices on such equipment. That could reduce pollution abatement in other regions, however, Demailly and Quirion (2012) do not include such mechanisms.

Although subsidies to pollution abatement have long been proposed as a measure to limit emissions (Lerner 1972; Fredrikson 1998), to our knowledge abatement subsidies have not been analyzed as a countermeasure towards emissions leakage. We take downstream support policies to include all kinds of subsidies to the use of abatement technologies by polluting firms. Examples of technologies may be more efficient ironmaking processing, alternative aluminum reduction technologies, improved catalyst technologies, and carbon capture technologies for industries such as cement and steel.

Upstream policies comprise all types of support to upstream firms supplying abatement technologies. The number of firms supplying a particular abatement technology may be small, especially if the environmental problem in question is relatively new, such that the available abatement technologies are still under patent protection. The subsidies could be direct production subsidies, or indirect subsidies to crucial inputs such as R&D or production capital. While such subsidies are offered in many countries, to our knowledge, they are not advocated as a countermeasure towards leakage. Our finding that they should be used in particular when we have emissions leakage is a key takeaway of the paper.

We begin by presenting the model and the different effects of upstream and downstream subsidies. Then we compare three cases. First, we look at the symmetric case in which both regions adopt the optimal symmetric emissions tax and technology subsidies. Then, we look at the case in which the emissions tax is asymmetric, but in which Region 1 aims to maximize global welfare by its technology policy. Finally, we analyze the case in which Region 1 only considers its own welfare, and sets technology policy strategically.

2 The model

The structure of the model is as follows: The world is divided into two regions, one domestic region (Region 1) and one foreign region (Region 2). There is one global downstream market for some industrial product, for which production leads to emissions of some pollutant that may have cross-border damages (e.g. GHG emissions). The downstream market consists of firms located and owned in each of the regions, and competition is perfect. There is one global upstream market for abatement equipment with a single price. In the upstream market, competition is imperfect, and for simplicity we assume that there is one firm located and owned in each of the two regions.[1]

In the first stage of the game, the government in Region 1 decides upon and announces its abatement technology policies, given the environmental policies in Region 1 and 2 *and* the environmental technology policies in Region 2. We consider two different types of environmental technology policy: The government can subsidize abatement expenditures by the downstream firms, and it can subsidize the costs of the upstream technology firms.

In the second stage of the game, the technology firms compete in Cournot fashion to supply abatement technology to the downstream industries in both countries. Thus, the upstream technology firms both export abatement equipment and supply their domestic market. Cournot competition is chosen because we believe that firms supplying a particular type of patented equipment first determine production capacity and then decide on the price.[2]

[1] In Section 8 we discuss the effects of assuming perfect instead of imperfect competition upstream.

[2] To simplify the analysis, we assume that the technology firms offer homogeneous technology equipments, meaning

The downstream industries are internationally competitive, and we assume that they sell their output on a global market with one world market price. Both industries are subject to an emissions tax (or part of a larger emissions trading market), which differs across regions.

In order to solve the model in a straightforward manner, we use explicit functional forms. Moreover, in order to highlight the leakage issue, we assume initially that downstream demand is completely inelastic. Thus, if one of the downstream industries become less competitive and reduces its output, the reduction in output will be completely replaced by the other industry. We relax this latter assumption in a later section.

2.1 The downstream industries

We treat the downstream industry in region i as one representative firm. For each firm, production (q_i) is a Cobb-Douglas function of energy inputs (g_i), which may also include other feedstocks causing emissions, and a fixed factor (k_i), such as land or sunk capital. In other words, $q_i = g_i^{\frac{1}{2}} k_i^{\frac{1}{2}}$. Let us normalize $k_i = 1$, so output is in essence a function of energy use, exhibiting diminishing returns: $q_i = g_i^{\frac{1}{2}}$. Equivalently, the total energy requirement for a given level of output is $g_i = q_i^2$. Industrial emissions are assumed to be proportional to energy use, but that ratio may be reduced by investment in abatement equipment (x_i). Specifically, let emissions from industry i take the form $e_i = g_i/(x_i + \epsilon)$, where $\epsilon > 0$ is a scaling parameter. Thus, we rewrite emissions in region i as a function of output and abatement equipment:

$$e_i = \frac{q_i^2}{x_i + \epsilon}, \ i = 1, 2 \tag{1}$$

that the only thing that matters for the downstream firm is how much emissions are reduced and how much the equipment costs. This implies that there is only one technology price. In reality, technology equipments may differ somewhat in other respects, in which case Cournot competition in heterogenous goods would be more appropriate. All our main results hold with this assumption, too.

Business as usual emissions are given q_i^2/ϵ. Note that emissions are convex in output, and that there are decreasing returns to abatement; i.e., $\frac{\partial^2 e_i}{\partial q_i^2} > 0$ and $\frac{\partial^2 e_i}{\partial x_i^2} > 0$. We find these assumptions to be a reasonable representation for an industry consisting of many firms, most likely producing with technologies of different vintages.

The representative firm faces a competitive product price of P, an international energy price of c, a region-specific emissions tax t_i, an international price for abatement equipment w, of which $(1-\eta_i)$ is the share of abatement costs paid by the firm in region i (the government pays the share η_i). The rental payments for the fixed factor is a fixed cost that shall be ignored.

The price-taking firm chooses output and abatement equipment to maximize profits, π_i^D:

$$\pi_i^D = Pq_i - cg_i - w(1-\eta_i)x_i - t_i e_i$$

The first-order condition for output reveals a linear, upward-sloping supply curve in each region, in which the slope depends on the emissions tax and abatement response (inserting from (1)):

$$P = 2\left(c + \frac{t_i}{x_i + \epsilon}\right) q_i$$

The first-order condition for abatement equipment trades off the savings in emissions tax payments with the cost of abatement equipment:

$$x_i = \sqrt{\frac{t_i}{w(1-\eta_i)}} q_i - \epsilon \qquad (2)$$

We assume that in the reference scenario, emissions prices in both regions are sufficiently large as to exclude negative abatement incentives.

Substituting into the expression for emissions,

$$e_i = \sqrt{\frac{w(1-\eta_i)}{t_i}} q_i \equiv \theta_i q_i. \tag{3}$$

Note that for a given subsidy rate, emissions tax and world market price of abatement equipment, emissions are proportional to output. We denote the region specific proportional factor by θ_i. Note that sufficient conditions for $\theta_1 < \theta_2$ are $t_1 > t_2$ and $\eta_1 \geq \eta_2$.

Inserting (2) into the first-order condition for output, we see that equilibrium marginal production costs are

$$P = 2\left(cq_i + \sqrt{w(1-\eta_i)t_i}\right) = 2\left(cq_i + t_i\theta_i\right)$$

As mentioned, we assume initially that downstream demand is completely inelastic and equal to Q.[3] In the market equilibrium, downstream price P must be equal to marginal costs in both regions; i.e., $P = 2\left(cq_1 + t_1\theta_1\right) = 2\left(cq_2 + t_2\theta_2\right)$, implying $q_2 = q_1 + (t_1\theta_1 - t_2\theta_2)/c$. Moreover, total supply must equal total demand ($q_1 + q_2 = Q$), leading to the following equilibrium output of the downstream industries:

$$q_1 = \frac{1}{2}Q\left(1-\alpha\right); \quad q_2 = \frac{1}{2}Q\left(1+\alpha\right) \tag{4}$$

where $\alpha = (t_1\theta_1 - t_2\theta_2)/(cQ)$ is the loss in market share due to excess emissions payments relative to energy costs. In other words, $q_2/Q - q_1/Q = \alpha$. Thus, output is decreasing to the extent that per-unit emissions payments at home $t_1\theta_1$ exceed those abroad $t_2\theta_2$.

[3] This convention is common in the trade literature for analyzing trade diversion; see, e.g., Meade (1955).

2.2 The upstream industry

Consider first the demand for abatement equipment. The demand function Y can be found from summing (2) over the two regions, and inserting for q_i from (4). We then obtain:

$$Y = \frac{A}{\sqrt{w}} - B \tag{5}$$

where $A = \left[\sqrt{\frac{t_1}{(1-\eta_1)}} + \sqrt{\frac{t_2}{(1-\eta_2)}}\right] \frac{Q}{2} > 0$ and $B = \left(\frac{\sqrt{(1-\eta_1)t_1} - \sqrt{(1-\eta_2)t_2}}{2c}\right)\left(\sqrt{\frac{t_1}{(1-\eta_1)}} - \sqrt{\frac{t_2}{(1-\eta_2)}}\right) + 2\epsilon$.

Note that (5) is a downward sloping, convex demand curve, and that $\frac{\partial A}{\partial \eta_1} > 0$ and $\frac{\partial B}{\partial \eta_1} < 0$.

We then turn to the supply of abatement equipment. As mentioned before, the two upstream technology firms supply their home market as well as the foreign market. Let y_i denote the supply of the firm in Region i. We assume that the supply of abatement equipment takes place at constant unit costs $(1-\gamma_i)\rho$, where ρ is the unit production costs and γ_i denotes the upstream technology subsidy rate.

For any set of policies $(\eta_1, \eta_2, \gamma_1, \gamma_2)$, total abatement will be the result of a Cournot game. Upstream firm 1 sets quantity y_1, while upstream firm 2 sets quantity y_2. Both firms maximize profits:

$$\pi_i = [w - (1-\gamma_i)\rho]\, y_i = \left[\frac{A^2}{(y_1 + y_2 + B)^2} - (1-\gamma_i)\rho\right] y_i,$$

where we inserted from (5). The first order condition for profit maximization upstream is then:

$$\frac{\partial \pi_i}{\partial y_i} = \frac{A^2}{(Y+B)^3}\,[y_j - y_i + B] - (1-\gamma_i)\rho = 0 \tag{6}$$

where both A and B depend on η_1 and η_2. The two equations (for $i = \{1,2\}$) in (6) yield the equilibrium values of $y_1(\eta_1, \eta_2, \gamma_1, \gamma_2)$ and $y_2(\eta_1, \eta_2, \gamma_1, \gamma_2)$ and together with the demand function (5) yield the equilibrium price $w(\eta_1, \eta_2, \gamma_1, \gamma_2)$. In the Appendix we show that the profit functions of the upstream firms are concave, and that the Nash equilibrium is unique. Moreover, by scaling the parameter ϵ in the emissions function (1), we ensure that reaction curves are downward sloping.

3 Effects of abatement subsidies

3.1 Upstream

First, we analyze how equilibrium abatement and the technology price depend on the level of the downstream abatement subsidy. We then have the following proposition:

Proposition 1 *If the government in Region 1 increases its downstream subsidy rate η_1, the market price of abatement equipment w increases, and supply of abatement equipment in both regions (y_1 and y_2) may or may not increase.*

Proof. See Appendix A. ■

The intuition behind the result is that subsidizing abatement investments in Region 1 makes demand for abatement less price elastic. The upstream technology firms responds by increasing their price-cost margin. In the extreme case they do not increase their supply, however, in our simulations we get increased supply. Note that as long as the upstream firms recieve no or identical upstream subsidies, they will adjust their output by the same amount.

We then turn to the upstream subsidy. Since the equilibrium is unique, we can apply general Cournot theory, in particular, we have the following proposition:

Proposition 2 *If the government in Region 1 increases its upstream subsidy rate γ_1, y_1 increases, y_2 decreases and the price w decreases.*

Proof. See Appendix A. ■

If the unit cost of one of the upstream firms falls, that firm increases output. This causes the marginal revenue of the other firm to fall, and the other firm to decrease its output. Total output of abatement technology will still increase since the direct cost effect on output is larger than the indirect effect through marginal revenue. Thus, the new market price will be lower than the old market price.

Note from Proposition 1 and 2 that the two types of technology policy have opposite effects on the price of abatement equipment w.

3.2 Downstream

Next, we look at the downstream effects of a change in η_1. We can then show the following proposition:

Proposition 3 *If Region 1 increases its downstream subsidy rate η_1, the downstream firm in Region 1 increases its output and use of abatement equipment, while the downstream firm in Region 2 decreases its output and use of abatement equipment.*

Proof. See Appendix A. ■

Note that the foreign industry reduces its use of abatement both due to the increase in price and due to the reduced output.

Second, we consider the effects of the upstream subsidy, where we have the following proposition:

Proposition 4 *If Region 1 increases its upstream subsidy rate γ_1, both downstream firms increase their use of abatement equipment. Moreover, the downstream firm in Region 1 increases its output, while the downstream firm in Region 2 decreases its output, if and only if average emissions payments are higher in Region 1 (α is positive).*

Proof. See Appendix A. ■

From the expressions in Appendix A we find that the upstream subsidy has similar effects on abatement in each region, in proportion to $1/\theta_i$, i.e., the inverse of the emissions intensity. The production effects are different, however. When the price of abatement equipment falls, the downstream firm that is subject to the highest emissions tax stands most to gain. Since the price of abatement equipment falls, both industries do more abatement for given outputs and consequently, emissions per unit of output decreases for both industries. Emissions will then also decline, since total production is unchanged, emissions intensities are uniformly lower, and more production is shifted to the lower intensity region. This is in stark contrast to the result of an increase in the downstream subsidy.

We are now ready to consider leakage and welfare effects of technology policies in Jurisdiction 1, taking into account the findings in Propositions 1-4.

4 Emissions leakage

Emissions leakage occurs whenever efforts by one country to reduce emissions leads to increased emissions in other countries. Our point of departure is that we have asymmetric environmental regulation. Does this lead to emissions leakage?

Leakage from unilateral carbon pricing has been extensively studied in the literature, both analytically and numerically (see e.g. Hoel 1996, and Böhringer et al. 2010). Thus, we will focus on leakage from abatement subsidies here. However, it is worth mentioning that the effects on emissions in Region 2 not only depend on the effects on output, but also on the technology price effect, which may go in either direction (see Appendix A).

The effects on emissions in Region 2 from the two technology subsidies are given by (see Appendix A):

$$\frac{de_2}{d\eta_1} = \frac{\theta_2}{4} Q (1+2\alpha) \frac{dw/d\eta_1}{w} - \frac{t_1\theta_2\theta_1}{4c(1-\eta_1)} \tag{7}$$
$$\frac{de_2}{d\gamma_1} = \frac{\theta_2}{4} Q (1+2\alpha) \frac{dw/d\gamma_1}{w}$$

Consider first the effects of the upstream technology subsidy. We know from Proposition 4 that the subsidy decreases the technology price ($dw/d\gamma_1 < 0$), which increases the use of abatement equipment in Region 2. Furthermore, we know that downstream output in Region 2 decreases as long as $\alpha > 0$, i.e., if average emissions payments in Region 1 are higher than in Region 2. Thus, foreign emissions decrease unambiguously with the upstream subsidy if $t_1(1-\eta_1) \geq t_2(1-\eta_2)$.

From Proposition 3 we know that the downstream subsidy increases the technology price ($dw/d\eta_1 > 0$), leading to less output (second term) and less abatement (first term) in Region 2. Hence, the effect of the downstream subsidy on foreign emissions is ambiguous.

We summarize these last results in the following proposition:

Proposition 5 *An upstream subsidy reduces foreign emissions if emissions payments are not higher in Region 2 ($\alpha \geq 0$), while a downstream subsidy may either increase or decrease foreign emissions.*

We notice that leakage effects depend crucially on how much the technology price responds to the subsidies. If the price response is small, foreign emissions will likely decline also with a downstream subsidy. We give a numerical example in which leakage is increased, however. For governments, it may be tempting to offset the effect of a higher emission tax by offering an abatement subsidy such that $(1-\eta_1)t_1$ is kept constant. However, this is likely to increase emissions leakage since the price of abatement technology is affected by such a policy.

The effects on global emissions follow to some degree the effects on foreign emissions as stated in the proposition above. An upstream subsidy unambiguously decreases global emissions (irrespective of α), while a downstream subsidy has ambiguous effects on global emissions (see Appendix A for details).

5 Globally optimal abatement technology policies

In order to have a benchmark, we start by looking at global welfare. Since downstream demand is fixed, consumer surplus is irrelevant; the price of the downstream good is merely a transfer between consumers and producers. Similarly, the abatement technology revenue is a transfer between downstream and upstream suppliers. Let Ω represent the gross surplus from the downstream good. Global welfare thus collapses to a question of minimizing total production costs and emissions damages, where τ denotes the shadow cost of emissions:

$$W = \Omega - (q_1)^2 \left(\frac{\tau}{(x_1 + \epsilon)} + c \right) - (q_2)^2 \left(\frac{\tau}{(x_2 + \epsilon)} + c \right) - \rho \left(y_1 + y_2 \right) \tag{8}$$

The second and third terms are downstream costs including the environmental costs, while the last term is the cost of abatement technology. Differentiating W we get:

$$\begin{aligned} dW = & -2q_1 \left(\frac{\tau}{(x_1 + \epsilon)} + c \right) dq_1 + (q_1)^2 \frac{\tau}{(x_1 + \epsilon)^2} dx_1 \\ & -2q_2 \left(\frac{\tau}{(x_2 + \epsilon)} + c \right) dq_2 + (q_2)^2 \frac{\tau}{(x_2 + \epsilon)^2} dx_2 - \rho \left(dx_1 + dx_2 \right) \\ = & \, 2 \left[(t_1 - \tau)\theta_1 - (t_2 - \tau)\theta_2 \right] dq_1 + \left[\frac{\tau}{t_1}(1 - \eta_1)w - \rho \right] dx_1 + \left[\frac{\tau}{t_2}(1 - \eta_2)w - \rho \right] dx_2 \end{aligned} \tag{9}$$

Here we have used that $dq_2 = -dq_1$, and that $dy_1 + dy_2 = dx_1 + dx_2$. Moreover, we have used the FoCs for the downstream industries with respect to x_i.

5.1 The symmetric case

First, we consider the **symmetric** case, where both regions have the same policy, i.e., $\eta_1 = \eta_2$, $\gamma_1 = \gamma_2$, and $t_1 = t_2 \leq \tau$. This implies that $q_1 = q_2$ (and thus $dq_i = 0$), $x_1 = x_2$, and $y_1 = y_2$. Thus, there is no emissions leakage. The welfare differential then writes:

$$dW = \left(\frac{\tau}{t}(1-\eta)w - \rho\right)(dx_1 + dx_2) = \left(\frac{\tau}{t}(1-\eta)w - \rho\right)dY \tag{10}$$

We know from before that $dY/d\eta > 0$ and $dY/d\gamma > 0$. If $\eta = \gamma = 0$, the parenthesis in (10) is positive, and thus dW has the same sign as dY. It then follows that it is optimal to introduce a strictly positive subsidy, either downstream or upstream (or both). If $t = \tau$, the only remaining externality is the imperfect competition upstream. Then the subsidies should be increased until $(1-\eta)w = \rho$, i.e., until the downstream producers pay exactly the unit costs of producing the technology. A social planner is indifferent whether the downstream or the upstream subsidy (or both) is increased, as they both increase Y without shifting market shares. If $t < \tau$, the subsidies should be increased further, i.e., until $(1-\eta)w = \frac{t}{\tau}\rho < \rho$. That is, if the emissions externality is not fully internalized, the technology subsidy should be increased to compensate for this. Note that since $\frac{\partial w}{\partial \eta} > 0$, it may be necessary to increase η more than expected up-front.

Proposition 6 *With symmetric policies and no emissions leakage, the government is indifferent between using upstream or downstream subsidies.*

Clearly, introducing a cost of public funds could modify this result as the upstream subsidy directly reduces w, while the downstream subsidy increases w, and hence, the total spending on the subsidy could be higher (see the numerical simulations below).

5.2 The asymmetric case

Second, we consider our main case where the two regions have **different tax rates**, i.e., $t_2 < t_1 \leq \tau$ and where $\eta_2 = \gamma_2 = 0$. This implies that $q_1 < q_2$ when there are no subsidies i.e. $\eta_1 = \gamma_1 = 0$. We assume that only Region 1 has a technology policy, and that it aims to maximize global welfare. Moreover, we consider one type of subsidy at the time.

For evaluating the optimal downstream subsidy, we can rewrite condition (9) in the following manner:

$$\frac{\partial W}{\partial \eta_1} = 2\left[c(q_2 - q_1) + \tau\left(\theta_2 - \theta_1\right)\right]\frac{\partial q_1}{\partial \eta_1} + \left[\frac{\tau(1-\eta_1)}{t_1}w - \rho\right]\frac{\partial x_1}{\partial \eta_1} + \left[\frac{\tau}{t_2}w - \rho\right]\frac{\partial x_2}{\partial \eta_1} = 0 \qquad (11)$$

The first term in (11) is strictly positive when there are no subsidies; increasing the downstream market share of Region 1 is beneficial due to lower marginal production costs (first term) and lower marginal emissions (second term). The second term is also positive as $w > \rho$ and $t_1 \leq \tau$. This reflects that it is beneficial to increase abatement in Region 1 due to exploitation of market power and possibly due to a too low emission tax even in Region 1. On the other hand, the third term is negative. Although emissions are priced too low in Region 2, and it is beneficial to stimulate the use of abatement technologies in that region, this cannot be done by a downstream subsidy in Region 1. A downstream subsidy reduces x_2 due to lower market share and higher price of abatement technology. Hence, the last term in (11) is negative for all η_1.

For the downstream subsidy we therefore obtain the following proposition:

Proposition 7 *A positive downstream subsidy is optimal if and only if the negative effect on welfare of less use of abatement technology in Region 2 is dominated by the positive effect on welfare from more production with less emission intensity at home, and from more use of abatement technology* *at home.*

In the numerical simulations we find that a downstream subsidy may be optimal as long as the emisson tax abroad is not too low. If the emission tax abroad is low, abatement is highly valuable on the margin, and thus discouraging foreign abatement hampers global welfare to a larger degree.

For the optimal upstream subsidy we have the following first order condition:

$$\frac{\partial W}{\partial \gamma_1} = 2\left[c(q_2 - q_1) + \tau\left(\theta_2 - \theta_1\right)\right]\frac{\partial q_1}{\partial \gamma_1} + \left[\frac{\tau(1-\eta_1)}{t_1}w - \rho\right]\frac{\partial x_1}{\partial \gamma_1} + \left[\frac{\tau}{t_2}w - \rho\right]\frac{\partial x_2}{\partial \gamma_1} = 0 \qquad (12)$$

Note that the terms in brackets in (12) are the same as the terms in brackets in (11). However, the upstream subsidy increases not only q_1 and x_1, but also x_2. Hence, $\frac{\partial W}{\partial \gamma_1}$ is strictly positive when $\eta_1 = \gamma_1 = 0$. Then, it is optimal to increase the upstream subsidy at least until one of the brackets become negative. Since we cannot have $q_1 = q_2$ as long as $(1-\eta_1)t_1 > (1-\eta_2)t_2$, this can only occur with $(1-\eta_1)w < \rho$, i.e. the price of technology is below its unit cost (if $\eta_1 = 0$). As a result, we state the following proposition:

Proposition 8 *With no downstream subsidy, if Region 1 aims to maximize global welfare, it should always provide an upstream subsidy.*

6 Strategic policies

Lets turn to the **regional welfare perspective**, where we still assume $t_2 < t_1 \leq \tau$. In this case, the single nation cares only about its own surplus and costs. Product revenues are not merely transfers between domestic consumers and producers to the extent that there are net imports. Assume that downstream consumption in Region 1 amounts to a market share μ of total consumption. Furthermore, we assume that Region 1 still evaluates the cost of emissions at the global optimal rate τ, which is equal to t_1.

The welfare expression for Region 1 can be expressed in the following way, where Ω_1 is gross consumer surplus in Region 1:

$$W_1 = \Omega_1 + P\left((1-\mu)q_1 - \mu q_2\right) - (q_1)^2\left(\frac{t_1}{(x_1+\epsilon)} + c\right) - (q_2)^2\frac{t_1}{(x_1+\epsilon)} + w\left(y_1 - x_1\right) - \rho y_1 \quad (13)$$

Region 1 now wants to maximize producer surplus both upstream and downstream taking into account both terms of trade effects $P\left((1-\mu)q_1 - \mu q_2\right)$ and $w\left(y_1 - x_1\right)$ in addition to emissions leakage $-(q_2)^2\frac{t_1}{(x_1+1)}$.

Differentiating W_1 we get:

$$\begin{aligned} dW_1 = & dP\left((1-\mu)q_1 - \mu q_2\right) + P\left((1-\mu)dq_1 - \mu dq_2\right) \\ & -2q_1\left(\frac{t_1}{(x_1+\epsilon)} + c\right)dq_1 + (q_1)^2\frac{t_1}{(x_1+\epsilon)^2}dx_1 \\ & -2q_2\frac{t_1}{(x_2+\epsilon)}dq_2 + (q_2)^2\frac{t_1}{(x_2+\epsilon)^2}dx_2 \\ & +\left(w-\rho\right)dy_1 - wdx_1 + \left(y_1 - x_1\right)dw \end{aligned}$$

Below, in order to simplify, we disregard downstream terms of trade effects as these have been discussed extensively before in the trade literature, see e.g. Meade (1955). We therefore assume $\mu = q_1/Q$ in equilibrium. Then the first term cancels out. Again we use that $dq_1 = -dq_2$ and $\frac{t_1(q_1)^2}{(x_i+\epsilon)^2} = (1-\eta_1)w$ (FoC for minimizing wrt, x_1). We also use that $p - q_1 - \frac{2q_1t_1}{(x_1+\epsilon)} = p - q_1 -$

$2\sqrt{(1-\eta_1)wt_1} = 0$. Thus, we have for the downstream subsidy:

$$\frac{\partial W_1}{\partial \eta_1} = -t_1\left(\frac{2q_2}{(x_2+\epsilon)}\right)\frac{\partial q_2}{\partial \eta_1} + \left[\frac{\tau(1-\eta_1)}{t_1}w - \rho\right]\frac{\partial x_1}{\partial \eta_1} + \left[t_1\frac{(q_2)}{(x_2+\epsilon)^2}\right]\frac{\partial x_2}{\partial \eta_1} + [w-\rho]\left[\frac{\partial y_1}{\partial \eta_1} - \frac{\partial x_1}{\partial \eta_1}\right] + [y_1 - x_1]\frac{\partial w}{\partial \eta_1} \tag{14}$$

Note that the three first terms in (14) are similar to the three terms in (11) from the global case. The two first term are positive: Region 1 would like the downstream industry in Region 2 to reduce its output since then environmental costs are reduced, and Region 1 would like increased use of abatement equipment at home since there is a mark-up and the tax rate may be set too low. As in (11) the third term is negative: A downstream subsidy decreases the use of abatement equipment in Region 2, and hence, increases emissions and regional environmental costs.

The two last terms in (11) only appear in the strategic case. They are both negative, since profit from the sales of abatement equipment is shifted abroad. With respect to the second last term, we must have $\frac{\partial y_1}{\partial \eta_1} - \frac{\partial x_1}{\partial \eta_1} < 0$. Only the polluting industry in Region 1 increases its use of abatement equipment. However, the increase in demand is covered by both the domestic and the foreign upstream firm, and hence, $\frac{\partial y_1}{\partial \eta_1} - \frac{\partial x_1}{\partial \eta_1} < 0$. With respect to the last term, when $t_1 > t_2$ and $\gamma_1 = \gamma_2 = 0$, we must have $x_1 > x_2$ and $y_1 = y_2$. Hence, Region 1 is a net importer of abatement equipment, and thus a price increase hurts Region 1.

For the downstream subsidy in the case of strategic policy we therefore obtain the following proposition:

Proposition 9 *A positive downstream subsidy is optimal if and only if the negative effect on welfare from less use of abatement technology in Region 2 and from shifting profit abroad is dominated by the positive effect on welfare from less production with high emission intensity abroad, and from* *more use of abatement technology at home.*

In the strategic case, it is much harder to find parameter combinations in the numerical simulations that yield a positive downstream subsidy. But what about the upstream subsidy?

For derivative of w_1 with respect to γ_1 we have

$$\frac{\partial W_1}{\partial \gamma_1} = -t_1 \left(\frac{2q_2}{(x_2+\epsilon)} \right) \frac{\partial q_2}{\partial \gamma_1} + \left[t_1 \frac{(q_2)}{(x_2+\epsilon)^2} \right] \frac{\partial x_2}{\partial \gamma_1} + \left[\frac{\tau(1-\eta_1)}{t_1} w - \rho \right] \frac{\partial x_1}{\partial \gamma_1} + [w-\rho] \left[\frac{\partial y_1}{\partial \gamma_1} - \frac{\partial x_1}{\partial \gamma_1} \right] + [y_1 - x_1] \frac{\partial w}{\partial \gamma_1} \tag{15}$$

Compared to (14) all three first terms are positive since $\partial x_2/\partial \gamma_1 > 0$. Furthermore, the fourth term is also positive. Only the upstream firm in region 1 increases its output if γ_1 goes up, while both downstream industries increase their use of abatement. Hence, we must have $\partial y_1/\partial \eta_1 - \partial x_1/\partial \eta_1 > 0$. Finally, the fifth term is also likely positive. As above we argue that $x_1 > x_2$ since $t_1 > t_2$. If $\gamma_1 = \gamma_2$, $y_1 = y_2$, and $x_1 > y_1$. However, for an upstream subsidy we have $\partial w/\partial \gamma_1 < 0$. Given that there is no downstream subsidy, we thus have the following proposition:

Proposition 10 *If Region 1 maximizes regional welfare, it should always provide an upstream subsidy.*

Thus, we get the same result as in the global case. This suggests that upstream subsidies are a more robust recommendation than downstream subsidies.

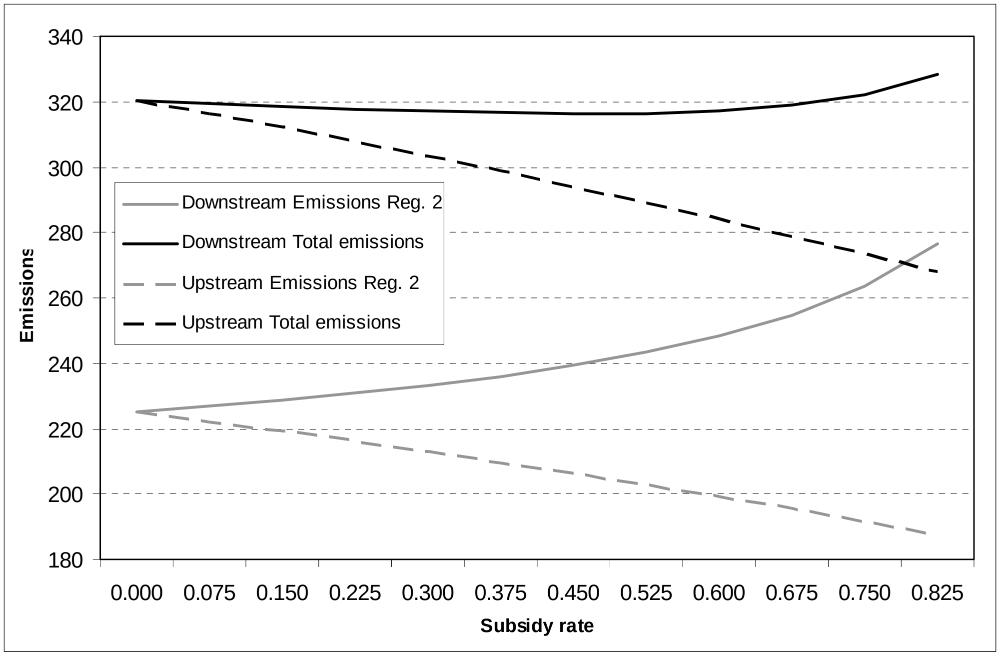

Figure 1 Effects of abatement subsidies on emissions

7 Numerical simulations

In order to illustrate our findings we have carried out a series of simulations. Below we show some examples. In the simulations, we assume global marginal damages from emissions are $\tau = 6$, while $t_1 = 5$ and $t_2 = 1$. Total abatement costs constitute around 10% of total costs. First, we compare the effects on emissions for downstream and upstream subsidies at different subsidy rates, see Figure 1. The dashed lines represent upstream subsdies. We distinguish between total emissions in black and emissions abroad in grey.

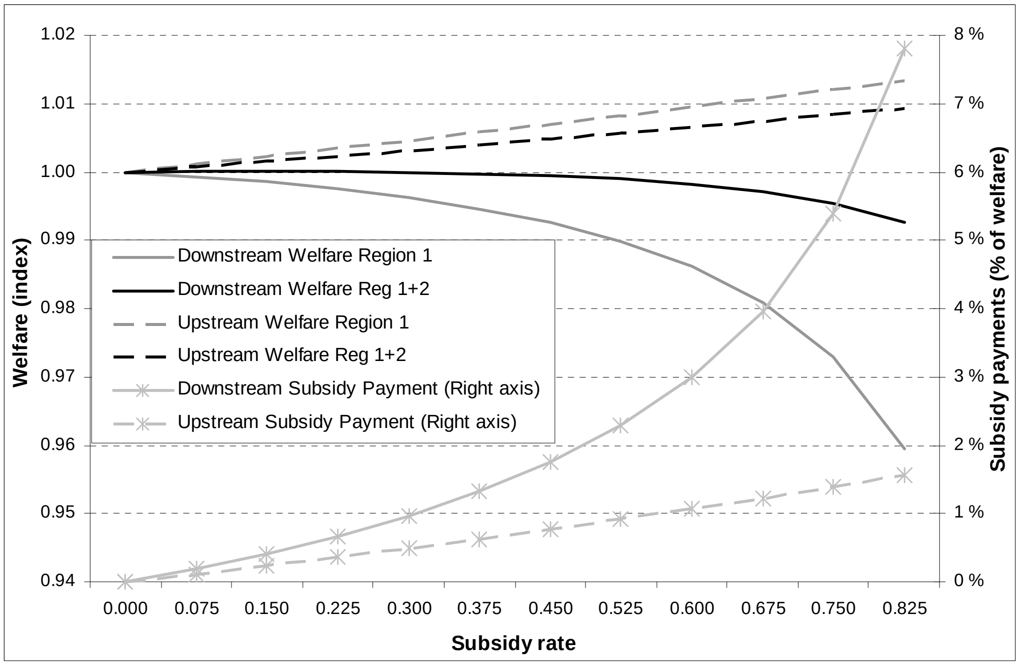

Figure 2 Effects of abatement subsidies on welfare and subsidy payments

Note first that a downstream subsidy strictly increases emissions abroad (emissions in Region 2). Note that for high subsidy rates, they also increase total emissions (the black line at the top). On the contrary, upstream subsidies strictly decrease both total emissions and emissions abroad (the two dashed lines). With a higher tax rate in Region 2, one may find that total emissions strictly decrease in the downstream subsidy, but emissions in Region 2 still seem to increase.

We then look at the effects on welfare in Figure 2, comparing one instrument at a time. As above, dashed lines represents upstream subsdies, but now we distinguish between global welfare in black and Region 1 welfare in grey.

We have normalized the welfare levels to 1 for zero subsidies. Note first that a downstream subsidy strictly decreases Region 1 welfare. Hence, it is never optimal from a strategic point of view to subsidize downstream. Note that for higher downstream subsidy rates, they also decrease global welfare. On the contrary, upstream subsidies strictly increase both global welfare and Region 1 welfare. If the government combines the use of both instruments, we find that a downstream subsidy is not optimal at all.

In the figure we also display the subsidy payments from the government in Region 1, relative to Region 1 welfare, in the two cases. The figure clearly shows that downstream subsidies are far more expensive for the government than upstream subsidies, for a given subsidy rate. Thus, if cost of public funds are taken into account, the case for downstream subsidies becomes even worse.

8 Extensions

We conduct some additional analysis to explore the robustness of our results to our baseline assumptions.

8.1 Elastic demand downstream

We have made some simplifying assumptions in order to arrive at our results. For instance, our assumption about completely inelastic demand downstream could of course be criticized. We have therefore solved the model with a simple linear demand curve downstream: $P = M - m(q_1 + q_2)$, which gives the following equilibrium output of the downstream industries:

$$q_1 = \frac{M}{2m+1}\left[2m + 1 - \alpha + \frac{2t_2\theta_2}{M}\right]; \quad q_2 = \frac{M}{2m+1}\left[2m + 1 + \alpha - \frac{2t_1\theta_1}{M}\right] \tag{16}$$

where $\alpha = \frac{2(m+1)t_1\theta_1 - 2(m+1)t_2\theta_2}{M}$. As for the completely inelastic demand case, it is the per-unit emission payments $t_i\theta_i$ that matters.

Demand for abatement Y is given by:

$$Y = \frac{\bar{A}}{\sqrt{w}} - \bar{B}$$

where $\bar{A}$ and $\bar{B}$ play the same role as A and B above.[4] As above we must have $\frac{\partial \bar{A}}{\partial \eta_1} > 0$, while $\frac{\partial \bar{B}}{\partial \eta_1} \leq 0$. Hence, we must also have $\frac{\partial w}{\partial \eta_1} > 0$ and $\frac{\partial w}{\partial \gamma_1} < 0$. Thus, we can use nearly all the results derived above: $\frac{\partial q_1}{\partial \eta_1} > 0$, $\frac{\partial q_2}{\partial \eta_1} < 0$, $\frac{\partial x_1}{\partial \eta_1} > 0$ and $\frac{\partial x_2}{\partial \eta_1} < 0$. Further, that: $\frac{\partial x_1}{\partial \gamma_1} > 0$, $\frac{\partial x_2}{\partial \gamma_1} > 0$, $\frac{\partial q_1}{\partial \gamma_1} > 0$.

The only thing that changes is that the sign on $\frac{\partial q_2}{\partial \gamma_1}$ is ambiguous. Before we had $dq_1 = -dq_2$, and hence, $\frac{\partial q_2}{\partial \gamma_1} < 0$ since $\frac{\partial q_1}{\partial \gamma_1} > 0$. With elastic downstream demand the downstream price may be nearly unaffected by the decrease in the price of abatement, and we may have $\frac{\partial q_2}{\partial \gamma_1} > 0$ due to the upstream price effect $\frac{\partial w}{\partial \gamma_1} < 0$. Moreover, in the welfare expression consumer surplus will now depend on both kinds of subsidies.

We conjecture that as long as $\frac{\partial q_2}{\partial \gamma_1} < 0$ the results above still holds. This conjecture is confirmed by additional numerical simulations we have performed. For a large range of different levels of m, the qualitative results are the same as in Figure 1 and 2.

8.2 R&D

Upstream subsidies are often granted as R&D subsidies, rather than subsidies to the production of abatement technology equipment. Here we show one way of incorporating R&D effort as an endogenous variable in our model. We assume that upstream firms do not set R&D levels strategically. Moreover, we assume that costs *before* any R&D is carried out, are given as $(\zeta_0 - \zeta_i)y_i^2$ where y_i is output of pollution abatement equipment as before.The parameter ζ_0 is an exogenous

[4] Note that $\bar{A} = \left[\sqrt{\frac{t_1}{(1-\eta_1)}} + \sqrt{\frac{t_2}{(1-\eta_2)}}\right] \frac{M}{2m+1}$ and $\bar{B} = 2\epsilon + \frac{2m+2}{2m+1}(t_1 + t_2) - \frac{2m}{2m+1}\sqrt{\frac{t_1}{(1-\eta_1)}}\sqrt{\frac{t_2}{(1-\eta_2)}}(2 - \eta_2 - \eta_1)$.

parameter representing the initial technology, and ζ_i is a choice variable for the upstream firm. Finally, the costs of R&D are given by the function $\frac{\zeta_i}{\zeta_0-\zeta_i}$.[5]

The total costs of supplying y_i units of equipment is then $(\zeta_0 - \zeta_i)y_i^2 + \frac{\zeta_i}{\zeta_0-\zeta_i}(1-\gamma_i)$ where the regulator subsidizes a share γ_i of R&D costs. The expression for total costs should be minimized with respect to ζ_i in order to find the opimal level of R&D as function of y_i. Then by inserting for the optimal level of R&D $\zeta_i^*(y_i)$, we obtain the reduced form costfunction $c_i(y_i)$ of the upstream firms:

$$c_i(y_i) = 2\sqrt{(1-\gamma_i)\zeta_0}y_i - (1-\gamma_i) \tag{17}$$

First, note that (17) is very similar to the expression we used for upstream costs above, i.e., costs were equal to $(1-\gamma_i)\rho y_i$. We see that when R&D efforts are endogenous, the upstream firm has constant marginal costs. Second, note that the constant marginal cost still depends negatively on the R&D subsidy rate and still does not depend on the downstream subsidy rate.[6] It then follows that all our derivations above regarding the effects of the different subsidies must carry directly over.

In the welfare expressions the costs of the upstream subsidy will naturally also differ: The cost of an upstream production subsidy is $\gamma_i \rho y_i$, while the cost of an upstream R&D subsidy is $\gamma_i \left[\sqrt{\frac{\zeta_0}{1-\gamma_i}}y_i - 1\right]$.[7] Again note that the expressions are very similar, among others, they are both linear in y_i. Thus, we still get that the conclusions with respect to the downstream subsidy are ambiguous, while the conclusions with respect to the upstream R&D subsidy are unambiguously

[5] The rationale behind the convex costfunction could be that pollution abatement equipment needs to be installed *in situ* and that this cost varies with the geographical location of the polluting firm.

[6] Since a downstream subsidy increases y_i, it also increases the amount of R&D and reduces cost. However, it does not affect the cost of the marginal installment.

[7] This can again be found by inserting for the optimal level of R&D $\zeta_i^*(y_i)$ in the expression for R&D subsidy costs $\frac{\zeta_i}{\zeta_0-\zeta_i}\gamma_i$.

positive (as long as the downstream subsidy is not in use). It is also easy to replicate the results given in Figure 1 and 2 with endogenous R&D and an R&D subsidy.

8.3 Perfect competition upstream

We have argued that imperfect competition upstream is a realistic assumption, given that both emissions regulations and advanced technologies are fairly new. Nevertheless, it is interesting to ask whether our results would change if we rather assumed perfect competition upstream. In the Appendix we show that most of our qualitative results carry over if we assume perfect competition and convex production costs upstream. In particular, the effects on the technology price are the same, and thus also the effects on leakage. The main difference is that the strategic effect, from a regional perspective, naturally disappears.

9 Conclusion

In a context of carbon leakage concerns and a lack of political will to price carbon emissions to the full extent of the social costs, many countries have turned to abatement technology policies as both complements to and substitutes for emissions pricing. We consider how best to target abatement technology subsidies. We conclude that a more robust recommendation can be made for upstream subsidies than for downstream subsidies. The results are to a large extent driven by the property in our model that a downstream subsidy increases the world market price of abatement equipment, and that an upstream subsidy has the opposite effect. As a consequence, while both types can address some underprovision of abatement, downstream subsidies tend to exacerbate leakage problems.

We have used explicit functional forms for both the emissions of the downstream industry and for production costs of the downstream industry. With more general forms, we would not be able to pin down the comparative statics effects of the two types of subsidies. We will, however, argue that the effects we have discovered are more general than our model suggests. Increased demand for abatement equipment in one country spurred by an abatement subsidy will tend to increase the price of abatement equipment. This again will tend to reduce the use of abatement equipment in the region not having a similar incentive, which has negative consequences from a global point of view.

Intuition from this model can also be used to speculate on the effectiveness of alternative measures. For example, how might upstream abatement subsidies compare with output-based allocation of emission quotas? Output-based allocation of emission quotas work in very much the same way as an output subsidy. Thus, output-based allocation will have no direct effect on foreign industries' abatement technology choices, and will likely not give local upstream abatement technology firms an advantage. Moreover, we can show that in our model they increase abatement technology prices, and may therefore fail to reduce emissions leakage.

We have not considered terms of trade effects downstream. Clearly, including terms of trade effects could alter our conclusions in the strategic case. There is no reason to believe that the ambiguity with respect to downstream subsidies would disappear. It is the unambiguous conclusion with respect to upstream subsidies that might be affected. Our simulation results suggest that it would not.

References

[1] Böhringer, C., Fischer, C. and K.E. Rosendahl. 2010. The Global Effects of Subglobal Climate Policies, *The B.E. Journal of Economic Analysis & Policy* 10(2) (Symposium): Article 13.

[2] Copenhagen Accord. 2009. http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf

[3] David, M. and B. Sinclair-Desgagné. 2010. Pollution Abatement Subsidies and the Eco-Industry, *Environ Resource Econ* 45: 271-282

[4] Demailly D. and P. Quirion. 2006. CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: Grandfathering vs. output-based allocation, *Climate Policy* 6: 93-113.

[5] Fischer, C. and A.K. Fox. 2012. Comparing Policies to Combat Emissions Leakage: Border Tax Adjustments versus Rebates. *Journal of Environmental Economics and Management* 64: 199–216 (September).

[6] Fredriksson, P.G. 1998. Environmental policy choice: Pollution abatement subsidies, *Resource and Energy Economics* 20: 51-63.

[7] Golombek, R. and M. Hoel. 2004. Unilateral Emissions Reductions and Cross-Country Technology Spillovers. *Advances in Economic Analysis & Policy* 4 (2): Article 3.

[8] Greaker, M. and K.E. Rosendahl. 2008. Environmental policy with upstream pollution abatement technology firms, *Journal of Environmental Economics and Management* 56: 246-259.

[9] Greaker, M. 2006. Eco-labels, Trade and Protectionism, *Environmental and Resource Economics* 33: 1-37.

[10] Hoel, M. 1996. Should a carbon tax be differentiated across sectors? *Journal of Public Economics* 59: 17-32.

[11] Lerner, A. P. 1972. Pollution abatement subsidies, *American Economic Review* 62: 1009-1010.

[12] Meade, J.E. 1955. *The Theory of Customs Unions*. Amsterdam: North-Holland.

[13] Millock, K. and C. Nauges. 2006. Ex Post Evaluation of an Earmarked Tax on Air Pollution, *Land Economics* 82: 68–84.

[14] Mæstad, O. 1998. On the efficiency of Green Trade Policy. *Environmental and Resource Eco-*

nomics 11: 1-18.

[15] Mæstad, O. 2001. Efficient Climate Policy with Internationally Mobile Firms, *Environmental and Resource Economics* 19: 267-284.

[16] Requate, T. 2005. Timing and Commitment of Environmental Policy, Adoption of New Technology, and Repercussions on R&D, *Environmental and resource Economics* 31: 175-199.

[17] World Trade Organization. 2011. Harnessing trade for sustainable development and a green economy, Geneva, Switzerland.

A The Cournot equilibrium

The first order conditions for a profit maximum upstream can be written:

$$\frac{\partial \pi_i}{\partial y_i} = \frac{A^2}{(Y+B)^3}\left[y_j - y_i + B\right] - (1-\gamma_i)\rho = 0$$

In equilibrium we must have $y_j - y_i - B > 0$. For the second-order conditions we have:

$$\frac{\partial^2 \pi_i}{(\partial y_i)^2} = -\frac{4A^2}{(Y-B)^4}\left[y_j - \frac{1}{2}y_i + B\right] < 0$$

The terms in brackets must be positive around the Nash equilibrium. The cross derivatives are given by:

$$\frac{\partial^2 \pi_i}{\partial y_j \partial y_i} = -\frac{2A^2}{(Y-B)^4}\left[y_j - 2y_i + B\right]$$

Here, the terms in brackets must not necessarily be positive. If $(y_j - 2y_i - B)$ is positive, it is easy to see that $\left|\frac{\partial^2 \pi_i}{(\partial y_i)^2}\right| > \left|\frac{\partial^2 \pi_i}{\partial y_j \partial y_i}\right|$. If on the other hand, $(y_j - 2y_i - B)$ is negative, we have $\left|\frac{\partial^2 \pi_i}{(\partial y_i)^2}\right| > \left|\frac{\partial^2 \pi_i}{\partial y_j \partial y_i}\right|$ as long as $y_j - y_i + B > 0$. Since B is given by $2\epsilon + t_1 + t_2 - \sqrt{\frac{t_1}{(1-\eta_1)}}\sqrt{\frac{t_2}{(1-\eta_2)}}(2-\eta_2-\eta_1)$, we can scale ϵ such that $y_j - 2y_i + B > 0$ holds. Hence, the equilibrium will be unique e.g. $\Delta = \frac{\partial^2 \pi_1}{(\partial y_1)^2}\frac{\partial^2 \pi_2}{(\partial y_2)^2} - \frac{\partial^2 \pi_1}{\partial y_2 \partial y_1}\frac{\partial^2 \pi_2}{\partial y_1 \partial y_2} > 0$.

Denote $(1-\gamma_1)\rho$ by c_1, and consider a small change in c_1. We expand the FoCs:

$$\frac{\partial^2 \pi_1}{(\partial y_1)^2}dy_1 + \frac{\partial^2 \pi_1}{\partial y_2 \partial y_1}dy_2 + dc_1 = 0$$
$$\frac{\partial^2 \pi_2}{\partial y_1 \partial y_2}dy_1 + \frac{\partial^2 \pi_2}{(\partial y_2)^2}dy_2 = 0$$

These can be solved, and we have:

$$\frac{dy_1}{dc_1} = \frac{\frac{\partial^2 \pi_2}{(\partial y_2)^2}}{\Delta} < 0,\ \frac{dy_2}{dc_1} = -\frac{\frac{\partial^2 \pi_2}{\partial y_1 \partial y_2}}{\Delta} > 0$$

Since, $\left|\frac{\partial^2 \pi_i}{(\partial y_i)^2}\right| > \left|\frac{\partial^2 \pi_i}{\partial y_j \partial y_i}\right|$, we have $\left|\frac{dy_1}{dc_1}\right| > \left|\frac{dy_2}{dc_1}\right|$. Thus, a decrease in cost for one of the firms, will increase total output and decrease the world market price of abatement equipment.

A.1 Proof of Proposition 1

Adding the first-order conditions (6) for both regions, we have:

$$\frac{2A^2B}{(Y+B)^3} = (2-\gamma_1-\gamma_2)\rho$$
$$Y = \left(\frac{2A^2B}{(2-\gamma_1-\gamma_2)\rho}\right)^{\frac{1}{3}} - B$$

Substituting this expression into (5) and rearranging, we get:

$$w = \left(\frac{A(2-\gamma_1-\gamma_2)\rho}{2B}\right)^{\frac{2}{3}}. \tag{18}$$

Remember that $\frac{\partial A}{\partial \eta_1} > 0$ and $\frac{\partial B}{\partial \eta_1} \leq 0$. From 18, we then see that $sign\left[\frac{\partial w}{\partial \eta_1}\right] = sign\left[B\frac{\partial A}{\partial \eta_1} - A\frac{\partial B}{\partial \eta_1}\right] > 0$, so w is increasing in η_1. This may or may not lead to increased output of abatement equipment by the upstream firms. Differentiating through the demand function $Y = \frac{A}{\sqrt{w}} - B$ we obtain:

$$\frac{\partial Y}{\partial \eta_1} = \frac{\frac{\partial A}{\partial \eta_1}}{2\sqrt{w}} - \frac{\partial B}{\partial \eta_1} - \frac{A}{2w\sqrt{w}}\frac{\partial w}{\partial \eta_1}$$

where the last term is negative.■

A.2 Proof of Proposition 2

The proof follows directly from (18), as both A and B are independent of γ.

A.3 Proof of Proposition 3

To see the change in downstream production, we totally differentiate (4), using the definition of α:

$$dq_i = \left((\theta_j dt_j - \theta_i dt_i) - (d\theta_i t_i - d\theta_j t_j)\right)/(2c).$$

Furthermore, from the definition of θ_i in (3) we have:

$$d\theta_i = \frac{\partial \theta_i}{\partial w}dw + \frac{\partial \theta_i}{\partial t_i}dt_i + \frac{\partial \theta_i}{\partial \eta_i}d\eta_i = \frac{1}{2}\theta_i\left(\frac{dw}{w} - \frac{d\eta_i}{(1-\eta_i)} - \frac{dt_i}{t_i}\right).$$

Let $\widehat{w}_i = w(1-\eta_i)$, so $d\widehat{w}_i/d\eta_i = (1-\eta_i)dw/d\eta_i - w$. Logically, $d\widehat{w}_i/d\eta_i < 0$; the net abatement cost in region i must be decreasing in its own subsidy. Although w increases in the downstream subsidy (see Proposition 1), it cannot outweigh the direct effect of the subsidy in region i; else, demand for abatement would fall in both regions, which contradicts the price rise in abatement equipment due to demand pressure. Hence, we get:

$$\frac{dq_1}{d\eta_1} = \frac{1}{4c}\left(t_2\theta_2\frac{dw/d\eta_1}{w} - t_1\theta_1\frac{d\widehat{w}_1/d\eta_1}{\widehat{w}_1}\right) > 0$$
$$\frac{dq_2}{d\eta_1} = -\frac{dq_1}{d\eta_1} < 0$$

Next, recall that abatement is $x_i = q_i/\theta_i - \epsilon$. Thus, $dx_i = dq_i/\theta_i - d\theta_i/\theta_i(q_i/\theta_i)$, implying:

$$\frac{dx_1}{d\eta_1} = \frac{1}{\theta_1}\left(\frac{dq_1}{d\eta_1} - \frac{q_1}{2}\frac{d\widehat{w}_1/d\eta_1}{\widehat{w}_1}\right) > 0$$
$$\frac{dx_2}{d\eta_1} = \frac{1}{\theta_2}\left(-\frac{dq_1}{d\eta_1} - \frac{q_2}{2}\frac{dw/d\eta_1}{w}\right) < 0$$

This completes the proof of Proposition 3.■

A.4 Proof of Proposition 4

From the derivations in the proof of Proposition 3 above, we get:

$$\frac{dq_1}{d\gamma_1} = -\frac{1}{4}\alpha Q\frac{dw/d\gamma_1}{w}$$
$$\frac{dq_2}{d\gamma_1} = -\frac{dq_1}{d\gamma_1}$$

$$\frac{dx_1}{d\gamma_1} = \frac{1}{\theta_1}\left(\frac{dq_1}{d\gamma_1} - \frac{q_1}{2}\frac{dw_1/d\gamma_1}{\gamma_1}\right) = -\frac{Q}{4\theta_1}\frac{dw/d\gamma_1}{w} > 0$$
$$\frac{dx_2}{d\gamma_1} = \frac{1}{\theta_2}\left(-\frac{dq_1}{d\gamma_1} - \frac{q_2}{2}\frac{dw/d\gamma_1}{w}\right) = -\frac{Q}{4\theta_2}\frac{dw/d\gamma_1}{w} > 0$$

We see that $\frac{dq_1}{d\gamma_1} > 0$ if and only if $\alpha > 0$. (and vice versa for $\frac{dq_2}{d\gamma_1}$).■

A.5 Emissions effects

From $e_i = \theta_i q_i$, we have $de_i = \theta_i dq_i + d\theta_i q_i$. Thus,

$$de_i = \theta_i \frac{(\theta_j dt_j - \theta_i dt_i)}{2c} + \frac{t_j \theta_i}{2c} d\theta_j + d\theta_i (q_i - \frac{t_i \theta_i}{2c})$$

Since we are not considering changes in Region 2 policies, $dt_2 = 0$ and $d\eta_2 = 0$. The effects on foreign emissions are then:

$$\begin{aligned} de_2 &= \frac{\theta_2 \theta_1}{2c} dt_1 + \frac{t_1 \theta_2 \theta_1}{4c} \left(\frac{dw}{w} - \frac{d\eta_1}{(1-\eta_1)} - \frac{dt_1}{t_1} \right) + \frac{\theta_2}{2} \frac{dw}{w} \left(q_2 - \frac{t_2 \theta_2}{2c} \right) \\ &= \frac{\theta_2}{4} \left(\frac{\theta_1}{c} dt_1 - \frac{t_1 \theta_1}{c} \frac{d\eta_1}{(1-\eta_1)} + Q\left(1+2\alpha\right) \frac{dw}{w} \right) \end{aligned}$$

From this expression, we can derive (7), and also:

$$\frac{de_2}{dt_1} = \frac{\theta_2}{4} Q\left(1+2\alpha\right) \frac{dw/dt_1}{w} + \frac{\theta_2 \theta_1}{4c}$$

Here we see that foreign emissions are unambiguously rising with the home emissions tax if $dw/dt_1 > 0$. Essentially, raising t_1 will raise w if it increases overall demand for abatement technologies. This result is undoubtedly likely for a range of t_1, although if the policy gets too stringent, it may become easier to meet by shifting production. Specifically, $sign\left[\frac{\partial w}{\partial t_1}\right] = sign\left[\frac{\partial A}{\partial t_1} B - A \frac{\partial B}{\partial t_1}\right]$. For example, suppose emissions taxes are initially symmetric and no technology policy exists. In this case, $\frac{\partial A}{\partial t_1} = \frac{Q}{4\sqrt{t_1}}$, $\frac{\partial B}{\partial t_1} = 0$ and $B = 2\epsilon > 0$. Thus, we have an unambiguous situation where $dw/dt_1 > 0$. By continuity $\frac{\partial w}{\partial t_1}$ will be positive also for t_1 slightly above t_2, and possibly in a larger range of t_1 depending on ϵ. Thus, as Region 1 raises its emissions price above that in Region 2, emissions in Region 2 will rise until downstream production in Region 1 loses so much market share that additional increases in the emissions tax reduce that region's demand for abatement equipment.

Considering global emissions, let $\overline{\theta} = \frac{1}{2}\left((1-\alpha)\theta_1 + (1+\alpha)\theta_2\right)$ be average emissions in the two regions. Since total downstream production is fixed, changes in total emissions depend on the change in average emissions.

$$
\begin{aligned}
d\overline{\theta} &= \frac{1}{2}\left((1-\alpha)d\theta_1 + (1+\alpha)d\theta_2 + (\theta_2 - \theta_1)\left(\frac{\partial\alpha}{\partial\theta_1}d\theta_1 + \frac{\partial\alpha}{\partial\theta_2}d\theta_2\right)\right) \\
&= \frac{1}{2}\left(\left(1-\alpha+(\theta_1-\theta_2)\frac{t_1}{cQ}\right)d\theta_1 + \left(1+\alpha-(\theta_1-\theta_2)\frac{t_2}{cQ}\right)d\theta_2\right)
\end{aligned}
$$

Substituting the changes in individual emissions intensities and simplifying,

$$
\begin{aligned}
d\overline{\theta} &= \frac{1}{4}\left(\left(1-\alpha+(\theta_1-\theta_2)\frac{t_1}{cQ}\right)\theta_1\left(\frac{dw}{w} - \frac{d\eta_1}{(1-\eta_1)} - \frac{dt_1}{t_1}\right) + \left(1+\alpha-(\theta_1-\theta_2)\frac{t_2}{cQ}\right)\theta_2\left(\frac{dw/d\eta_1}{w}\right)\right) \\
&= \frac{1}{4}\left(\theta_1 + \theta_2(1-2\alpha)\right)\frac{dw}{w} - \frac{1}{4}\left(1 - \frac{(t_1-t_2)\theta_2}{cQ}\right)\theta_1\left(\frac{d\eta_1}{(1-\eta_1)} + \frac{dt_1}{t_1}\right)
\end{aligned}
$$

Since we are considering the situation where $\theta_2 - \theta_1 \geq 0$ and $t_1 \geq t_2$, we have: 1) The direct effect of an emissions tax in Region 1 is to lower global emissions, but the indirect effect of higher abatement equipment prices is to offset some of those reductions. 2) Similarly, the direct effect of a downstream subsidy is to lower global emissions, but again the indirect effect of raising abatement prices tends to raise emissions. 3) The only effect of the upstream subsidy is to lower abatement costs and therefore global emissions necessarily fall.

B Perfect competition upstream

We now explore the assumption about Cournot competition upstream may be driving our results. Instead of having two upstream firms, let us assume that abatement technology is supplied by two upstream industries; one in each region. These industries have costs $\frac{\rho(1-\gamma_i)}{2}(y_i)^2$, where γ_i is the upstream subsidy. Demand is still given $Y = \frac{A}{\sqrt{w}} - B$. In equilibrium the marginal cost of the two upstream industries must be equalized and equal to the price: $\rho(1-\gamma_1)y_1 = \rho(1-\gamma_2)y_2 = w$. Hence, market equilibrium in the upstream market implies:

$$\frac{w}{\rho(1-\gamma_1)} + \frac{w}{\rho(1-\gamma_2)} = \frac{A}{\sqrt{w}} - B \tag{19}$$

Differentiating through (19) we obtain:

$$\frac{dw}{d\eta_1} = \rho(1-\gamma_1)\frac{\frac{1}{\sqrt{w}}\frac{\partial A}{\partial \eta_1} + \frac{\partial B}{\partial \eta_1}}{1 + \frac{\rho(1-\gamma_1)}{\rho(1-\gamma_2)} + \rho(1-\gamma_1)\frac{A}{2\sqrt{w}w}} > 0$$

$$\frac{dw}{d\gamma_1} = \frac{-\frac{A}{\sqrt{w}} + B + y_2}{1 + \frac{\rho(1-\gamma_1)}{\rho(1-\gamma_2)} + \rho(1-\gamma_1)\frac{A}{2\sqrt{w}w}} < 0$$

Hence, we still have $\frac{\partial w}{\partial \eta_1} > 0$ and $\frac{\partial w}{\partial \gamma_1} < 0$. Assuming that $\frac{\partial[w(1-\eta_1)]}{\partial \eta_1} < 0$ as above, we can then use all the results derived above: $\frac{\partial q_1}{\partial \eta_1} > 0$, $\frac{\partial q_2}{\partial \eta_1} < 0$, $\frac{\partial x_1}{\partial \eta_1} > 0$ and $\frac{\partial x_2}{\partial \eta_1} < 0$. Further, that: $\frac{\partial x_1}{\partial \gamma_1} > 0$, $\frac{\partial x_2}{\partial \gamma_1} > 0$, $\frac{\partial q_1}{\partial \gamma_1} > 0$ and $\frac{\partial q_2}{\partial \gamma_1} < 0$. Hence, we conjecture that as long as $t_1 < \tau$ the results above still hold, while the use of both instruments becomes ambiguous when $t_1 = \tau$.