Robust technology policy against emission leakage: The case of upstream subsidies*

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Abstract

Asymmetric regulation of a global pollutant between countries can alter the competitiveness of industries and lead to emissions leakage, which hampers countries' welfare. In order to limit leakage, governments consider supporting domestic trade-exposed firms by subsidizing their investments in abatement technology. The suppliers of such 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.

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1 Introduction

Addressing the problem of a global pollutant is challenging, and made more so when regulatory regimes differ across jurisdictions. The prime example is the reduction of greenhouse gas (GHG) emissions. The United Nations Framework Convention on Climate Change (UNFCCC) explicitly states that countries have common but differentiated responsibilities (CBDR), putting greater regulatory burdens on developed than developing countries. This differentiation was made explicit in the Kyoto protocol, which divided countries into those with binding emissions limits (Annex I) and those without (Non-Annex I). At the meeting among the parties to the UNFCCC in Paris in December 2015, countries agreed to set GHG mitigation targets, but the stringency of the targets are not harmonized and vary substantially among countries.[1] Differentiated responsibilities between developed and developing countries is also a part of the Montreal Protocol on substances that deplete the ozone layer.

In the case of a global pollutant, marginal abatement costs should ideally be equalized across countries, in order to allocate abatement effort efficiently. For several reasons—like CBDR—this rule may not be implemented, but asymmetry in regulation between countries can then create problems beyond an inefficient allocation of abatement resources. Unilateral increases in the stringency of regulation can alter the competitiveness of industries and lead to *emissions leakage*. Emissions leakage occurs whenever efforts by one country to reduce emissions leads 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.

The literature on emissions leakage has identified three main ways of mitigating leakage associated with emissions pricing policies targeting the downstream regulated industries. One option is exempting the most trade-exposed, energy intensive industries, although the potential gains are limited relative to the lost emissions reduction opportunities (e.g., Böhringer, Carbone and Rutherford 2012). A second route would use production subsidies to counteract cost increases from emissions pricing for sensitive sectors, typically implemented through output-based rebating or "benchmarking" the allocation of emissions allowances. This method preserves the incentives to reduce emissions intensity, while avoiding emissions reduction through production relocation or conservation (Bernard, Fischer and Fox 2007; Fischer and Fox 2007). The third and theoretically more efficient option is to use border adjustments—that is, tariffs on embodied carbon, perhaps in combination with export refunds—in order to ensure that consumers of the downstream products face consistent pricing on the embodied emissions, regardless of the location of production (Hoel 1996; Mæstad 1998). While a broad legal consensus has emerged that border carbon adjustments can be designed to withstand

[1] http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx

a WTO challenge (Horn and Mavroidis 2011), resorting to such measures would be highly controversial in trade communities and of concern for developing countries, who would bear a greater burden (Böhringer, Fischer, and Rosendahl 2010).

In this paper we explore a fourth way to reduce emission leakage. According to the WTO, supporting the deployment and diffusion of green technologies is not hindered by WTO rules (WTO 2011). Although subsidies to pollution abatement have been proposed as a measure to limit emissions (e.g., Lerner 1972; Fredrikson 1998), they have not received the same attention in the emissions leakage literature; to our knowledge, this study is the first. Our research question is thus whether subsidies to pollution abatement technology should be used to limit emissions leakage.

In our study we take into account that the supply of abatement technology typically takes place in separate abatement technology firms see, e.g., Requate 2005; David and Sinclair-Desgagné 2005, 2010; Nimubona 2012; Schwartz and Stahn 2014. These papers do not treat the leakage issue. Moreover, unlike these papers, our focus is on technology policies and not on environmental policies (or trade policies as in Nimubona 2012). We therefore not only ask to what extent abatement subsidies should be used to limit emissions leakage, but also inquire into the design of the abatement technology subsidy scheme.

One option is to pay a part of the abatement costs of the downstream polluting industries. We focus on abatement costs that involves investment in new technology such as alternative metal smelting technologies, improved catalyst technologies, and carbon capture technologies for industries such as cement, refineries and steel. Subsidizing downstream would be the traditional route to follow cf. the three ways of mitigating emission leakage described above.

However, there exist another option, governments may increase their support of the upstream firms developing and supplying abatement technologies. The upstream 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 findings suggest that one can make a more robust recommendation for upstream subsidies than downstream subsidies. Downstream subsidies tend to increase global abatement technology prices, reducing pollution abatement abroad, and likely increasing emissions leakage. To our knowledge, this effect has not been discussed in the literature on emission leakage so far, and clearly, it could also be a side effect of production subsidies to polluting industries. By contrast, upstream subsidies reduce abatement technology prices, and hence also encourage emissions reductions abroad.

Competition in a particular abatement technology market may be imperfect, especially if the environmental problem in question is relatively new, such that the available abatement technologies are still under patent protection. In this case downstream subsidies come with an additional disadvantage; they do not provide domestic abatement technology firms with a strategic advantage and increase oligopoly profits abroad as well as at home. Upstream subsidies, on the contrary, shift oligopoly rents home, as they provide domestic abatement technology firms with a strategic advantage. Thus, a key takeaway of this paper is that upstream subsidies have more robust strategic and global benefits than downstream subsidies when we have emissions leakage.

Current policy, by contrast, seems to favor downstream subsidies. 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). Similarly, in Norway the government has established separate public funds financing both NOx and GHG abatement technology investment in polluting industries.

Much of the analysis of emission leakage show that policy designs matter (Fischer and Fox 2012; Böhringer, Bye, Fæhn and Rosendahl 2012), as does coalition size (Böhringer, Fischer, and Rosendahl 2012), and modeling assumptions (e.g., a recent Energy Modeling Forum exercise dedicated to border carbon adjustments: *Energy Economics* 34 Supplement 2). However, none of these studies include a separate eco-industry. Including the eco-industry opens up a strategic trade perspective on different kinds of abatement technology policies. Subsidies to oligopolistic firms is extensively studied in the trade literature (see for example Brander and Spencer, 1985, Eaton and Grossman, 1986, and Leahy and Neary, 1997), but it is difficult to apply the results from this literature directly to the case of export of pollution abatement equipment. The profit shifting motive for an upstream production subsidy is also present in our analysis. However, due to the asymmetric environmental policies, the subsidies have additional welfare effects both on domestic and foreign welfare.

Our paper also has similarities with Greaker and Rosendahl (2008) and David and Sinclair-Desgagné (2005). Both papers 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), and not present in David and Sinclair-Desgagné (2005). From a regional perspective, however, that could constitute an important aspect of an upstream support policy.

We begin by presenting the model and the different effects of upstream and downstream subsidies. Then we compare two cases. First, we look at the case in which Region 1 considers its own welfare (accounting for global emissions), and sets technology policy strategically. Then, we consider the case where subsidies in Region 1 are set in order to maximize global welfare. In Section 6 we discuss the effects of assuming an alternative market structure both downstream and upstream, and in Section 7 we conclude.

2 The model

The world is divided into two regions, one domestic region (Region 1) and one foreign region (Region 2). In each region there is a downstream polluting industry and upstream firms supplying pollution abatement technology. Pollution entails cross-border damages (e.g. GHG emissions). In the downstream market competition is perfect, and there are no barriers to trade. The upstream market producing the abatement technology also trades globally, but competition is imperfect.

The game proceeds in a context in which each region has adopted a tax on emissions t_i, equal to its private valuation of the social cost of emissions; thus, neither internalizes emission damages in the other region. For ease of discourse, we generally assume $t_1 > t_2 > 0$. In the first stage of the game, the government in Region 1 decides upon and announces its abatement technology policy, given the technology policy in the other region.

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. Cournot competition is chosen to reflect the situation in which firms supplying a particular type of patented equipment first determine production capacity, and then the price is determined in the market based on the produced quantity.

2.1 The downstream market equilibrium

First, we need to solve for the downstream market equilibrium and derive the implicit demand functions for abatement technology in each region. In order to simplify expressions, we assume that total global demand for the downstream product is constant at Q; in Section 6 we discuss the implications of relaxing this assumption.

Let emissions e_i from the downstream industry in each region be given by the following relationship:

$$e_i = e(q_i, x_i) \tag{1}$$

where q_i is output and x_i is the installed number of abatement equipments. Denoting derivatives $\partial e_i/dq_i = e_{iq}$ etc. we have: $e_{iq} > 0$, $e_{iqq} \geq 0$, $e_{ix} \leq 0$, $e_{ixx} > 0$ and $e_{iqx} \leq 0$, $i = 1, 2$. For end-of-pipe equipment, the cross-derivative e_{iqx} is zero, see for instance David and Sinclair-Desgagné (2005). For other types of abatement, such as changing process technology, the sign is most likely negative, see Greaker (2003).

Downstream firms are perfectly competitive, and they maximize revenues net of production and compliance costs, which are composed of emissions tax payments plus technology costs:

$$\max_{q_i, x_i} \{Pq_i - h(q_i) - t_i e(q_i, x_i) - (1 - \eta_i) w x_i\} \tag{2}$$

where P is the price on the downstream product, $h(q_i)$ are production costs (with $h', h'' > 0$), w is the price of abatement equipment and η_i is a region-specific subsidy to abatement equipment. By differentiating (2) with respect to x_i, and setting the derivative equal to zero, we obtain the demand for abatement equipment:

$$-e_{ix}(q_i, x_i) = \theta_i \tag{3}$$

where $\theta_i = (1 - \eta_i)w/t_i$ is the net cost of abatement relative to emissions. From this equation, we see the response of abatement equipment demand to price and production changes: $dx_i = -(d\theta_i + e_{ixq}dq_i)/e_{ixx}$. Thus, demand for abatement equipment is decreasing in θ_i, which is increasing in w, and decreasing in t_i and η_i. Demand is also increasing in output q_i provided that $e_{iqx} < 0$. For end-of-pipe equipment we therefore have $dx_i/dq_i = 0$.

Next, production occurs until total marginal costs equal the price:

$$P = h'(q_i) + t_i e_{iq}(q_i, x_i) \tag{4}$$

If we totally differentiate the four first-order conditions (3) and (4), with $q_1 + q_2 = Q$ (and fixed downstream demand), we have a system of five equations describing $\{dq_1, dq_2, dx_1, dx_2, dP\}$ as functions of the downstream policy or price changes. For a constant price of abatement equipment, we show in Appendix A that $\partial q_i/\partial t_i < 0$, $\partial q_j/\partial t_i > 0$, $\partial q_i/\partial \eta_i > 0$ and $\partial q_j/\partial \eta_i < 0$ for $i \neq j$. Thus, given equal subsidies, the industry with the lower emissions tax rate would have a higher market share, or given equal emissions taxes, the industry with the higher downstream abatement subsidy would have a higher market share.

Which region's industry gains market share from a change in the equipment price depends on the relative marginal abatement costs associated with additional output: if $(1 - \eta_1)dx_1/dq_1 > (1 - \eta_2)dx_2/dq_2$, then $dq_2/dw > 0 > dq_1/dw$. That is, if Region 1 spends more on abatement per additional unit of output, a higher equipment price will cause it to lose market share to Region 2. Because $t_1 > t_2$, we assume $dx_1/dq_1 \geq dx_2/dq_2$ for $\eta_1 = \eta_2$, and thus, $dq_2/dw \geq 0 \geq dq_1/dw$. However, for end-of-pipe equipment we have $dq_i/dw = 0$.

Since the two industries have identical production costs and emission abatement opportunities, asymmetric regulation of the global pollutant yields a non-optimal allocation of world production, which also results in emissions that are excessively high. Can an abatement technology subsidy improve on this situation? Before we answer this question, we must solve for the upstream market equilibrium.

2.2 The upstream Cournot equilibrium

For simplicity, we assume that there is one upstream firm located and owned in each of the two regions; in the numerical example later we relax this assumption. Further, we let the two firms have identical cost structures. Denote the supply of abatement technology by the upstream firms in the two regions by y_i, $i = 1, 2$. Further, let $Y = y_1 + y_2$. In equilibrium, total supply must equal total demand:

$$Y^D = x_1(q_1, \theta_1) + x_2(q_2, \theta_2) \tag{5}$$

where the abatement demand functions $x_i(q_i, \theta_i)$ are defined by (3) above. From (5) we can derive the inverse demand curve relevant for the upstream suppliers:

$$w = w(Y; t_1, t_2, \eta_1, \eta_2) \tag{6}$$

The change in the total quantity of abatement equipment demanded with respect to the price of abatement equipment is given from the right-hand side of (5):

$$\frac{dY^D}{dw} = \left[x_{1q}\left(q_1, \theta_1\right) - x_{2q}\left(q_2, \theta_2\right)\right] \frac{dq_1}{dw} + x_{1\theta}\left(q_1, \theta_1\right) \frac{1-\eta_1}{t_1} + x_{2\theta}\left(q_2, \theta_2\right) \frac{1-\eta_2}{t_2}$$

where we have used that $dq_1/dw = -dq_2/dw$.[2]. Let $\Delta = \left[x_q\left(q_1, \theta_1\right) - x_q\left(q_2, \theta_2\right)\right] \frac{dq_1}{dw}$. In most of the remainder of the paper, we will assume that $\Delta \approx 0$, so that small shifts in market share due to equipment price changes have neligible changes on total abatement demand. A commonly used sufficient (but not necessary) condition for this assumption to hold is that x denotes end-of-pipe abatement equipment characterized by $dq_i/dw = 0$.[3] Another would be to start from a symmetric equilibrium. However, even with less restrictive conditions these effects are of second order importance.[4]

Let $s = -dw/dY = -1/(dY/dw)$ be the downward slope of the inverse demand function. With $\Delta \approx 0$, we can then write:

$$\frac{dw}{dy_i} = -s = \frac{t_1 t_2}{t_2(1-\eta_1)x_{1\theta} + t_1(1-\eta_2)x_{2\theta}} < 0.$$

Since both terms in the denominator are negative, the demand curve for abatement equipment is downward sloping.

Let both upstream firms have constant unit costs $(1-\gamma_i)\rho$, where γ_i denotes the upstream technology subsidy. This subsidy may come in the form of direct subsidies, tax breaks, or even R&D support - essentially, anything that lowers marginal production costs. Total abatement will be the result of a Cournot game in which both firms maximize profits: $\left(w(Y; ..) - (1-\gamma_i)\rho\right) y_i$. The first-order conditions are given by:

$$w - sy_i - (1-\gamma_i)\rho = 0, \tag{7}$$

We assume that quantities are strategic substitutes, and that the second-order condition for profit maximization holds.[5]

[2] Note that since $q_1 + q_2 = Q$, we must have $dq_1/dw = -dq_2/dw$.

[3] See, e.g. David and Sinclair-Desgagné (2005), David et al. (2011) and Nimubona (2012) which all assume $e_{xq} = 0$ implying $dq_i/dw = 0$.

[4] When abatement and output interact, then $x_q(q_1, \theta_1) \geq x_q(q_2, \theta_2)$ when region 1 has the more ambitious set of policies, i.e., if $t_1 \geq t_2$ and/or $\eta_1 \geq \eta_2$. That is, when the industry is subject to a higher tax and/or larger subsidy, changes in output might have a larger effect on abatement demand. However, since the output effects on abatement demand pull in opposite directions, the net effect of this is likely dominated by the direct price effect on abatement demand in the two regions.

[5] This implies $\frac{dw}{dY} + \frac{d^2w}{dY^2} y_i = -2s - \frac{ds}{dw}\frac{dw}{dy_i} y_i = -s + \frac{ds}{dw} s y_i < 0$ or $\frac{ds}{dw} y_i < 1$. This condition also ensures that the second-order condition for profit maximization holds; that is, $2\frac{dw}{dY} + \frac{d^2w}{dY^2} y_i = -2s + \frac{ds}{dw} s y_i < 0$ or $\frac{ds}{dw} y_i < 2$.

Adding the first-order conditions, we derive total supply:

$$Y^S = \frac{2(w-\rho) + (\gamma_1 + \gamma_2)\rho}{s}. \tag{8}$$

and reveal the market share of firm i:

$$\frac{y_i}{Y} = \frac{1}{2} + \frac{\gamma_i - \gamma_j}{2(w-\rho) + (\gamma_i + \gamma_j)\rho}. \tag{9}$$

Since costs only differ if subsidies differ, the firm with the larger subsidy has the larger market share.

3 The effects of abatement technology policies

3.1 Upstream market

The effects of the upstream subsidy are in line with Cournot theory:

Proposition 1 *For the effects of an upstream subsidy we have:* $dw/d\gamma_i < 0$, $dY/d\gamma_i > 0$, $dy_i/d\gamma_i > 0$ *and* $dy_j/d\gamma_i < 0$.

Proof. See Appendix C. ■

Raising the upstream subsidy γ_i decreases the price of abatement equipment and increases total abatement equipment supply. Moreover, while the output of the upstream firm receiving the subsidy increases with γ_i, the output of the rival upstream firm decreases.

Neither the emissions taxes nor the downstream subsidies can influence the upstream market shares, y_i/Y, since there are no barriers to trade, and the two upstream firms face exactly the same world demand $w(Y; t_1, t_2, \eta_1, \eta_2)$. By rewriting (7) we see that changes to the Cournot Nash-equilibrium are transmitted only through the price elasticity of demand for abatement equipment, $El_{Y,w} = \left|\frac{dY}{dw}\frac{w}{Y}\right|$:

$$\frac{w - (1-\gamma_i)\rho}{w} = \frac{y_i/Y}{\left|\frac{dY}{dw}\frac{w}{Y}\right|} \tag{10}$$

In Appendix B we show that the absolute value of the price elasticity of demand for abatement equipment, $El_{Y,w}$, is decreasing in the downstream subsidy rates η_i as long as $\Delta \approx 0$ and the marginal return to abatement equipment e_x does not diminish too fast, that is, $e_{xx} \geq \theta_i e_{xxx}$ (in words; e_{xx} must not increase too much in x).

Note that, neither $\Delta \approx 0$ nor $e_{xx} \geq \theta_1 e_{xxx}$ is a necessary condition for $El_{Y,w}$ to be decreasing in the downstream subsidy rates η. We find this result rather intuitive: when the downstream emissions tax or abatement subsidy rate is increased, the polluting firms will be less sensitive to an increase in the price of abatement equipment, because the policies become relatively more important drivers of demand. Related results were found in David and Sinclair-Desgagné (2005), who showed that an emission tax increases the price of abatement.

As long as the price elasticity of demand for abatement equipment is decreasing in the downstream subsidy, it follows:

Proposition 2 *For the effects of a downstream subsidy we have:* $dw/d\eta_i > 0$, $dY/d\eta_i > 0$, $dy_i/d\eta_i > 0$ *and* $dy_j/d\eta_i > 0$.

Proof. When $|El_{Y,w}|$ decreases, the right-hand side of (10) will increase, and, consequently, the left-hand side in that expression has to increase; since $d(\frac{w-\rho}{w})/dw > 0$, the price must increase (see also Vives, 1999, p. 100). An increase in Y^S follows from the increase in w, however, market shares stay constant (see Appendix C for the rest of the effects). ■

The market price w and supply of abatement equipment Y both increase if one of the regions raises the downstream subsidy rate η_i. Moreover, both upstream firms will increase their supply of abatement equipment.

3.2 Downstream market

We now turn to the downstream market equilibrium effects of the subsidies. First, we consider the effects of the upstream subsidy on the downstream market equilibrium.

Proposition 3 *The effects of an upstream subsidy on the downstream market are:* $dP/d\gamma_i < 0$ *and* $dq_i/d\gamma_i > 0$, $dq_j/d\gamma_i < 0$ *if* $(1-\eta_i)dx_i/dq_i > (1-\eta_j)dx_j/dq_j$, *and* vice-versa.

Proof. See Appendix D. ■

The proposition follows from the fact that the price of abatement equipment decreases (see Proposition 1). A lower price of abatement equipment reduces the marginal costs of the downstream industries yielding a lower market equilibrium price. The lower price of abatement equipment also induces the downstream firm with the largest reduction in marginal cost to increase its output, while the other downstream firm will contract its output. As argued above we assume $dx_1/dq_1 \geq dx_2/dq_2$ for $\eta_1 = \eta_2$, and thus, $dq_1/d\gamma_i \geq 0 \geq dq_2/d\gamma_i$ when $\eta_1 = \eta_2$. Note also that for end-of-pipe equipment $dq_i/d\gamma_i$, $dq_j/d\gamma_i = 0$.

Assuming that the price elasticity of demand for abatement equipment is decreasing in the downstream subsidy, for the downstream market effects of a change in the downstream subsidy, we have the following proposition:

Proposition 4 *The effects of a downstream subsidy on the downstream market are:* $dq_i/d\eta_i > 0$, $dq_j/d\eta_i < 0$ *if* $dq_i/d\eta_i$ *given* w, *is greater than* $|dq_i/dw * dw/d\eta_i|$

Proof. See Appendix D. ■

The direct effect of the downstream subsidy η_i is to increase the output q_i of the downstream industry in Region i. However, the subsidy also increases the abatement equipment price w, and to the extent that $(1-\eta_i)dx_i/dq_i > (1-\eta_j)dx_j/dq_j$, this will lead to a contraction in output e.g. $dq_i/dw * dw/d\eta_i < 0$.

For the remainder of the paper we will assume that this indirect effect is dominated by the direct effect, and thus $dq_i/d\eta_i > 0$, $dq_j/d\eta_i < 0$. Note that for end-of-pipe equipment this always holds.

This time we cannot tell the effect on the downstream market equilibrium price P. On the one hand, marginal production costs go down for the industry receiving the subsidy, but, on the other hand, the price of abatement equipment increases implying that marginal production costs go up in the foreign industry.

3.3 Emissions leakage

In the remainder of the paper, we take as our point of departure that the price elasticity of demand for abatement equipment is decreasing in the downstream subsidy. Inserting the abatement demand functions $x_i(q_i, \theta_i)$ into the emissions functions (1) gives the equilibrium level of emissions:

$$e_i = e(q_i, x(q_i, \theta_i)) = \varepsilon(q_i, \theta_i) \tag{11}$$

For the relative cost of abatement, it is straightforward to show that $\varepsilon_{i\theta} = e_{ix}x_{i\theta} > 0$; that is, a higher price of abatement equipment, a lower emissions tax, or a lower abatement equipment subsidy, all increase emissions. The change in equilibrium emissions with respect to q_i is $\varepsilon_{iq} = e_{iq} + e_{ix}x_{iq}$. We assume $e_{iq} > |e_{ix}x_{iq}|$, and thus $\varepsilon_{iq} > 0$; in other words, we assume that emissions are *normal*, and not *inferior* inputs.[6]

Emissions leakage occurs whenever efforts by one country to reduce emissions lead to increased emissions in other countries. A well-established result from other literature is that unilateral emissions taxes tend to cause emissions leakage. In our model, the effects on emissions in Region 2 of a higher t_1 is then given by:

$$\frac{\partial \varepsilon_2}{\partial t_1} = \varepsilon_{2q}(q_2, \theta_2)\frac{dq_2}{dt_1} + \varepsilon_{2\theta}(q_2, \theta_2)\frac{1-\eta_2}{t_2}\frac{dw}{dt_1} > 0 \tag{12}$$

Emissions leakage may happen through two channels when t_1 rises. First, higher downstream costs at home tend to shift industrial output toward the foreign region – this is the standard leakage channel. Second, as demand for abatement equipment in Region 1 increases, the price of equipment most likely rises, leading to less abatement by the foreign industry.[7] Since we are looking at transboundary pollution, increased emissions from the other region reduces welfare in the region that increases its emissions tax.

Our first research question is whether abatement subsidies can be a countermeasure against carbon leakage. We first look at the effects of increasing η_1:

$$\frac{\partial \varepsilon_2}{\partial \eta_1} = \varepsilon_{2q}(q_2, \theta_2)\frac{dq_2}{d\eta_1} + \varepsilon_{2\theta}(q_2, \theta_2)\frac{1-\eta_2}{t_2}\frac{dw}{d\eta_1} \tag{13}$$

[6] See Greaker (2003) for a discussion of this topic.

[7] It can be shown that sufficient (but not necessary) conditions for both channels to be positive is that $|El_{Y,w}|$ is non-increasing in t_i, and $\eta_1 \approx \eta_2$.

Increasing the downstream subsidy has an ambiguous effect on foreign emissions. On the one hand, output is relocated from the low emissions tax region to the high emissions tax region which all other things equal reduces foreign emissions (i.e., $dq_2/d\eta_1 < 0$, $\varepsilon_{2q} > 0$). On the other hand, the subsidy increases the price of abatement equipment, which makes the remaining foreign industry buy less equipment and increase their emissions (i.e., $\varepsilon_{2\theta} > 0$). Thus, even with end-of-pipe abatement equipment, we cannot sign $d\varepsilon_2/d\eta_1$.

Turning to the upstream subsidy, we find that the effect of raising γ_1 is unambiguous as long as abatement is end-of-pipe and/or we have $\eta_1 = \eta_2$:

$$\frac{\partial \varepsilon_2}{\partial \gamma_1} = \varepsilon_{2q}(q_2, \theta_2)\frac{dq_2}{dw}\frac{dw}{d\gamma_1} + \varepsilon_{2\theta}(q_2, \theta_2)\frac{1-\eta_2}{t_2}\frac{dw}{d\gamma_1} \tag{14}$$

We have $dq_2/dw \geq 0$ for $\eta_1 = \eta_2$, since we then assume $x_{2q}(q_2, \theta_2) \leq x_{1q}(q_1, \theta_1)$. With end-of-pipe abatement equipment $dq_2/dw = 0$. The first term in (14) is thus zero or negative as $dw/d\gamma_1$ is negative. Furthermore, the second term in (14) is also negative as $dw/d\gamma_1 < 0$. Thus, we have $d\varepsilon_2/d\gamma_1 < 0$.

We conclude with the following proposition:

Proposition 5 *The upstream subsidy is more robust than the downstream subsidy with respect to reducing emissions leakage.*

In our numerical simulation in Section 5 we find that a downstream subsidy increases foreign emissions in all our scenarios, while an upstream subsidy always reduces foreign emissions. We are now ready to consider welfare effects of technology policies in Region 1, taking into account the findings above.

4 Effects on welfare

4.1 Strategic abatement technology policies

We start by looking at optimal technology policies when policy makers maximize *regional welfare*. Regional welfare includes gross regional surpluses minus production costs and own valuation of environmental costs due to global emissions. We assume that the regional emissions tax reflects this valuation. Note that, to the extent that there are net imports, regions can benefit from changes in the terms of trade (ToT).

Since downstream demand is fixed, gross consumer surplus in Region 1 is given. Let downstream consumption in Region 1 amount to half of total consumption. Assuming that Region 1 considers t_1 as the shadow cost of global emissions, the welfare for Region 1 can then be expressed in the following way:

$$\begin{aligned} W_1 = {} & \Omega_1 - P\frac{Q}{2} + Pq_1 - h(q_1) - wx_1 \\ & +(w-\rho)y_1 - t_1(\varepsilon_1 + \varepsilon_2) \end{aligned} \tag{15}$$

where Ω_1 is gross consumer surplus in Region 1. First, note that P, q_1, q_2, x_1, w, y_1, ε_1 and ε_2 are all functions of the policy variables t_i, η_i and

γ_i. Second, note that emissions taxes, downstream subsidies and upstream subsidies either paid or received by the firms and either received or paid by the government cancel out.

In order to analyze to what extent Region 1 should use downstream or upstream subsidies, we differentiate W_1 wrt. η_1 and γ_1. Further, we evaluate the sign on derivative of the welfare function for one instrument at the time, e.g., when looking at η_1 we assume $\gamma_1 = \gamma_2 = 0$ and *vice versa.* The derivative of Region 1's welfare with respect to the downstream subsidy is given by:

$$\begin{aligned} \frac{dW_1}{d\eta_1} &= \underbrace{(q_1 - \frac{Q}{2})\frac{dP}{d\eta_1}}_{\text{Downstream ToT}} + \underbrace{(y_1 - x_1)\frac{dw}{d\eta_1}}_{\text{Upstream ToT}} + \underbrace{(w - \rho)(\frac{dy_1}{d\eta_1} - \frac{dx_1}{d\eta_1})}_{\text{Profit Shifting}} \\ &+ \underbrace{(t_1 e_{1x} - \rho)\frac{dx_1}{d\eta_1}}_{\text{Domestic Abatement}} \underbrace{- t_1 \left[\varepsilon_{2\theta}\frac{1-\eta_2}{t_2}\frac{dw}{d\eta_1} - (\varepsilon_{2q} - \varepsilon_{1q})\frac{dq_1}{\eta_1}\right]}_{\text{Net Leakage}} \end{aligned} \tag{16}$$

where we use the notation $e_{1x} = \partial e(q_1, x_1)/\partial x_1$, $\varepsilon_{2\theta} = \partial \varepsilon(q_2, \theta_2)/\partial \theta_2$ etc.

The two first terms can be coined terms-of-trade (ToT) effects (see Mead 1955). We know that $q_1 - \frac{Q}{2} < 0$ for $\eta_1 = 0$, since Region 1 is a net importer of the downstream good as long as $t_2 < t_1$. However, as long as we do not know $dP/d\eta_1$ we cannot sign the downstream ToT effect.

The second term is negative as $\frac{dw}{d\eta_1} > 0$. As long as $\gamma_1, \gamma_2 = 0$, we have $y_1 = y_2$. Further, as $t_1 > t_2$ and $\eta_1 \geq \eta_2$, we must have $x_1 > x_2$, and hence, $y_1 - x_1 < 0$. Thus, upstream terms-of-trade becomes worse with a downstream subsidy.

The third term is the profit shifting effect. Again as long as $\gamma_1, \gamma_2 = 0$, we must have $\frac{dy_1}{d\eta_1} = \frac{dy_2}{d\eta_1}$. Moreover from Proposition 4 we know that $\frac{dx_1}{d\eta_1} > 0$, and $\frac{dx_2}{d\eta_1} < 0$. Hence, we must have $\frac{dy_1}{d\eta_1} < \frac{dx_1}{d\eta_1}$. Thus, oligopoly profit is shifted abroad since domestic consumption of abatement technology increases more than domestic production, and hence the term is negative.

The fourth term is positive as long as $t_1 e_{1x} > \rho$; it is socially optimal to to increase the use of abatement equipment at home as long as the marginal gain is larger than the marginal cost. This is the case since the downstream industry set $t_1 e_{1x} = (1 - \eta_1)w > \rho$ (for moderate downstream subsidy rates η_1).

We coin the fifth term "Net Leakage" since it includes the net emission effect of reallocating downstream output between the regions. Looking at the terms inside the bracket we have: First, a downstream subsidy increases the price of abatement leading to higher emission from Region 2. Second, downstream output decreases in Region 2 and increases in Region 1 ($dq_1/d\eta_1 > 0 > dq_2/d\eta_1$), which reduces emissions as emission from the last unit of output is likely lower in Region 1 (eg. $\varepsilon_{1q} < \varepsilon_{2q}$ when $t_1 > t_2$). Thus, in general, we cannot sign the fifth term, however, for end-of-pipe cleaning equipment $\varepsilon_{2q} = \varepsilon_{1q}$, and the term is negative.

To sum up, we have two ambiguous effects (ToT downstream and Net Leakage), one positive (Domestic Abatement) and two negative effects (ToT upstream and Profit Shifting), and consequently we cannot say whether use of the downstream subsidy increases welfare.

The derivative with respect to the upstream subsidy is given by:

$$\begin{aligned}\frac{dW_1}{d\gamma_1} =& \underbrace{(q_1 - \mu Q)\frac{dP}{d\gamma_1}}_{\text{Downstream ToT}} + \underbrace{(y_1 - x_1)\frac{dw}{d\gamma_1}}_{\text{Upstream ToT}} + \underbrace{(w-\rho)(\frac{dy_1}{d\gamma_1} - \frac{dx_1}{d\gamma_1})}_{\text{Profit Shifting}} \\ &+ \underbrace{(t_1 e_{1x} - \rho)\frac{dx}{d\gamma_1}}_{\text{Domestic Abatement}} \underbrace{- t_1 \left[\varepsilon_{2\theta}\frac{1-\eta_2}{t_2} + (\varepsilon_{2q} - \varepsilon_{1q})\frac{dq_2}{dw}\right]\frac{dw}{d\gamma_1}}_{\text{Net Leakage}}\end{aligned} \tag{17}$$

The first term in (17) is positive: The upstream subsidy improves terms of trade downstream since, with no downstream subsidy, Region 1 is a net importer of the downstream good and the price of this good decreases. Furthermore, the upstream subsidy also improves terms of trade upstream for values of γ_1 close to γ_2, as we then have $x_1 > y_1$ and $\frac{dw}{d\gamma_1} < 0$.

For the profit shifting effect, we have $\frac{dy_1}{d\gamma_1} - \frac{dx_1}{d\gamma_1} > 0$ since $\frac{dy_1}{d\gamma_1} > 0$, $\frac{dy_2}{d\gamma_1} < 0$, and $\frac{dx_1}{d\gamma_1}, \frac{dx_2}{d\gamma_1} > 0$. Thus, oligopoly profit is shifted home since domestic production of abatement technology increases more than domestic consumption. The fourth term is equivalent to the fourth term in (16). It is positive; the upstream subsidy increases the use of abatement equipment at home, which improves welfare as long as $w > \rho$. Lastly, net leakage effect is also positive since an upstream subsidy decreases emissions in Region 2 by lowering the price of abatement equipment. Moreover, as for the downstream subsidy, it reallocates downstream output to Region 1 which reduces emissions.[8] Thus, we have five positive effects.

Proposition 6 *Welfare in Region 1 improves if Region 1 implements a positive upstream subsidy.*

Increasing the upstream subsidy improves terms of trade upstream, shifts oligopoly profits home, increases the use of abatement equipment at home and reduces emissions abroad. A downstream subsidy has the opposite effects on the terms of trade upstream, shift oligopoly profits abroad, and an ambiguous effect on emissions abroad. Hence, we find a more robust recommendation for upstream subsidies than for downstream subsidies.

[8] We generally assume $x_q(q_1, \theta_1) > x_q(q_2, \theta_2)$ since $t_1 > t_2$. Then $dq_2/dw > 0 > dq_1/dw$; i.e., if region 1 spends more on abatement per additional unit of output, a higher equipment price will cause it to lose market share to region 2. Thus, both terms inside the bracket in the fifth term are positive, while $dw/d\gamma_1 < 0$.

4.2 Altruistic abatement technology policies

In the strategic trade literature—see for instance Brander and Spencer (1985)—supporting domestic firms is a kind of beggar-thy-neighbor policy. This may no longer hold when emissions leakage is an issue. Thus, in this section we ask the hypothetical question: What kind of technology policy would Region 1 implement if it is altruistic, that is, cares about welfare in both regions?

Since downstream demand is fixed, gross consumer surplus is given. Maximizing global welfare thus implies minimizing the sum of total costs (denoted TC) given that globally a quantity Q should be produced:

$$TC = h(q_1) + h(q_2) + \rho(x_1 + x_2) + (t_1 + t_2)(\varepsilon_1 + \varepsilon_2) \tag{18}$$

where the first two terms in (18) are downstream production costs in the two regions, the third term is upstream abatement technology costs in the two regions, and the fourth term is total environmental damages, where we assume that $t_1 + t_2$ denotes the global shadow cost of emissions. Revenues are simply transfers, so all prices, taxes and subsidy payments cancel out.

The technology policy then has two aims: First, unequal tax rates in the two regions imply inefficient allocation of downstream production. Second, imperfect competition and too low tax rates in both regions imply too little use of abatement technology.

In order to look at the effect of providing technology subsidies, we differentiate the social cost function TC wrt. η_1 and γ_1. Further, we evaluate the sign of the derivative of the cost function for one instrument at the time e.g. when looking at η_1 we assume $\gamma_1 = 0$ and *vice versa*. The change in total costs due to a change in η_1 is given by:

$$\begin{aligned} \frac{dTC}{d\eta_1} = & \underbrace{\left[h'(q_1) - h'(q_2)\right] \frac{dq_1}{d\eta_1}}_{\text{Production costs}} + \underbrace{\left[(t_1 + t_2)e_{1x} + \rho\right] \frac{dx_1}{d\eta_1}}_{\text{Abatement Reg. 1}} \\ & \underbrace{+\left[(t_1 + t_2)e_{2x} + \rho\right] \frac{x_{2\theta}}{t_2} \frac{dw}{d\eta_1}}_{\text{Abatement Reg. 2}} - \underbrace{(t_1 + t_2)(\varepsilon_{2q} - \varepsilon_{1q}) \frac{dq_1}{d\eta_1}}_{\text{Output emission effects}} \end{aligned} \tag{19}$$

where we use the notation $e_{1x} = \partial e(q_1, x_1)/\partial x_1$ etc.

With identical representative firms, downstream production costs are minimized when $q_1 = q_2$; therefore, total production costs decrease with η_1 as long as q_1 is smaller than q_2, as is the case when $t_1 > t_2$ in the absence of subsidies. Thus, with η_1 close to zero, the first term in (19) is negative.

The second term is negative for moderate values of η_1. When deciding its level of abatement x_1 the downstream industry in Region 1 sets $t_1 e_{1x} = (1 - \eta_1)w$. Since $t_1 + t_2 > t_1$ and $(1 - \eta_1)w > \rho$ for small η_1, the bracket $(t_1 + t_2)e_x + \rho$ is negative. As long as this is the case, too little abatement equipment is utilized also in Region 1, and the direct effect of a downstream subsidy is to improve on that $(dx_1/d\eta_1 > 0)$.

The third term in (19) is, however, positive. When deciding its level of abatement x_2 the downstream industry in Region 2 sets $t_2 e_x + w = 0$. Since $t_1 + t_2 > t_2$ and $w > \rho$, the bracket $(t_1 + t_2)e_x + \rho$ is negative. Moreover, we have $x_{2\theta} < 0$ and $dw/d\eta_1 > 0$, and the term is positive. The intuition is that too little abatement equipment is utilized due to mark-up pricing. A downstream subsidy exacerbates this inefficiency since the downstream subsidy then leads to a higher price of abatement equipment.

The fourth term in (19) is the effect on total emission from a reallocation of output from Region 2 to Region 1. As discussed above the sign on the term is positive, and thus this effect reduces total costs ($\varepsilon_{2q} > \varepsilon_{1q}$ and $dq_1/d\eta_1 > 0$). To sum up, there are three negative and one positive term in (19), and hence the effect of the downstream subsidy on global welfare is ambiguous. Due to the three cost reducing effects, we conjecture that a downstream subsidy performs better from an altruistic perspective. This is also confirmed in our numerical simulations.

The change in total costs from a change in γ_1 is:

$$\frac{dTC}{d\gamma_1} = \underbrace{\left[h'(q_1) - h'(q_2)\right] \frac{dq_1}{dw} \frac{dw}{d\gamma_1}}_{\text{Production costs}} + \underbrace{\left[(t_1 + t_2)e_{1x} + \rho\right] \frac{x_{1\theta}}{t_1} \frac{dw}{d\gamma_1}}_{\text{Abatement Reg. 1}} + \underbrace{\left[(t_1 + t_2)e_{2x} + \rho\right] \frac{x_{2\theta}}{t_2} \frac{dw}{d\gamma_1}}_{\text{Abatement Reg. 2}} - \underbrace{(t_1 + t_2)(\varepsilon_{2q} - \varepsilon_{1q}) \frac{dq_1}{dw} \frac{dw}{d\gamma_1}}_{\text{Output emission effects}} \tag{20}$$

As above we have $h'(q_1) < h'(q_2)$. Thus, the first term in (20) is negative since $dq_1/dw < 0$ and $dw/d\gamma_1 < 0$. The next two terms in (20) corresponds to the second and third term in (19). Of the same reasons as explained above $(t_1 + t_2)e_{(1/2)x} + \rho < 0$. Then, since $x_{(1/2)\theta} < 0$ and $dw/d\gamma_1 < 0$, both terms are negative. Finally, the net leakage is also negative as output is reallocated to Region 1 which on the margin has lower emissions per unit of output. Thus, we can conclude:

Proposition 7 *Global welfare improves if Region 1 implements a positive upstream subsidy.*

In many cases it may be optimal to use both subsidies e.g. both η_1 and γ_1 are positive. The downstream subsidy is likely more effective with respect to improving the allocation of downstream production, while only the upstream subsidy can deal with the insufficient use of abatement technology abroad.

What happens to the welfare of Region 2 when Region 1 uses an upstream subsidy? Region 2 will benefit from lower global emissions and lower costs on abatement equipment. On the other hand, the upstream terms of trade and profit shifting effects pull in the other direction, leaving the total effect on the welfare of Region 2 ambiguous.

Clearly, due to the profit shifting effect, Region 2 may also have incentives to use upstream subsidies. We can then use equation (20) to consider what happens if both regions use upstream subsidies. Since the unambiguous reduction in global costs is caused by $dw/d\gamma_1$ being negative, and $dw/d\gamma_2$ is also negative, use of upstream subsidies by Region 2 can only improve global welfare. This holds as long as the marginal value of emission reductions are greater than the marginal costs e.g. $(t_1+t_2)e_{2x}+\rho<0$. Hence, we conjecture that a central planner would choose to use upstream subsidies in both regions.

Below we present a numerical example in which we compare altruistic policies with strategic policies. We also look at the effect on Region 2's welfare.

5 Numerical example

In order to illustrate our findings we provide a numerical example. Let emission be given by $e_i = (q_i - x_i)^2/2 + x_i/2$, and production costs by $h(q_i) = q_i^2/2$. The whole model can then be solved explicitly.[9] The numerical example also allows us to consider the role of the degree of competition upstream by allowing for multiple upstream firms: m firms operate in Region 1 and n firms operate in Region 2. The optimal subsidies will depend on the difference in emissions tax levels, the configuration of upstream firms, and whether regional or global welfare is being maximized. In Figure 1, we have maximized the welfare of Region 1, and drawn the optimal combination of subsidies, γ_1 and η_1. We have also looked at different configurations of the upstream firms, and at different values of t_2. The higher the upstream subsidy in Region 1, and the lower the emissions tax in Region 2, the more likely it is that the foreign abatement technology firms exit the market due to the high upstream subsidy in Region 1. Without any restrictions on the subsidies, the optimal upstream subsidy becomes very high under some configurations; thus, we set an upper limit on this subsidy equal to ρ ($\gamma_1 \leq \rho$).

Figure 1 "Optimal combination of subsidies for Region 1"

Along the y-axis we measure the subsidies relative to the cost of providing abatement equipment (in fraction of the upstream cost ρ), while we measure the value of t_2 in percent of t_1 on the x-axis. We show the results for three different configurations. For instance, "1-3" implies that there are 1 upstream firm in Region 1 and 3 upstream firms in Region 2. We see that the optimal upstream subsidy is always positive and significantly higher than the downstream subsidy. This remains the case even though some upstream firms drop out of the market in many situations (e.g., for $t_2 < 0.75t_1$ for the configurations 2-2 and 3-1), in which case the profit shifting effect vanishes. Moreover, we find the corner solution of a 100% subsidy is optimal ($\gamma_1 = \rho$) for any t_2 with the configuration 1-3, and for low values of t_2 for the two other configurations. This confirms our main message in the paper that imposing

[9] See Appendix D for a complete derivation of the numerical model.

upstream subsidies is a more robust technology policy choice from a strategic perspective.

Next, note that the optimal downstream subsidy η_1 declines as the foreign tax rate t_2 decreases. At first thought this seems counter-intuitive, since the emissions leakage problem is more pronounced with a higher difference in emissions tax rates. However, the downstream subsidy on the margin exacerbates leakage more the lower is the tax rate abroad. Finally, note that the downstream subsidy is lowest if the upstream configuration is 1-3. The reason is that both the terms-of-trade effect and the profit shifting effect upstream is more negative in this case.

Why does Region 1 want to implement an upstream subsidy γ_1 which may be larger than the cost ρ? As long as the upstream price $(1-\eta_1)w$ is greater than the upstream cost ρ, there is too little use of abatement equipment in Region 1. Thus, when the downstream subsidy becomes low or even negative, we tend to get a very high upstream subsidy. In addition comes the beneficial effect from reduced emissions abroad which also drives the high upstream subsidy (see Figure 3).

In Figure 2 we look at the optimal subsidies from a global perspective. In this case we always get $\gamma_1 = \rho$, and we have not drawn γ_1 for any of the configurations. Note that in the altruistic case, the use of abatement equipment is too low for two reasons: The emissions tax in both regions falls short of marginal environmental damage $(t_1 + t_2)$, and the upstream price is higher than the upstream cost. This holds in particular in Region 2 in which a downstream subsidy is not implemented.

Figure 2 "Altruistic combinations of subsidies"

First, note that the downstream subsidy should be much higher in the altruistic case than in the regional case. The reason is that from the global perspective, downstream production should be equally split between the regions, and only the downstream subsidy can accomplish that.[10] As above, the optimal downstream subsidy η_1 declines the smaller is the foreign tax rate t_2. Again, the downstream subsidy on the margin increases emissions abroad more the lower is the tax rate abroad. Moreover, in our example this effect dominates the effect from the increased downstream production cost.

We have also looked at the effect on leakage with the 2-2 configuration of upstream firms. In Figure 3 the increase/reduction in foreign emissions is measured for different values of t_2. Here we consider one subsidy at a time.

Figure 3 "The effect on emissions leakage"

Note that for all t_2, the downstream subsidy increases emissions in Region 2 by around 3% compared to our baseline. Since for lower tax rates, emissions

[10] Note that for the emission function we use in the numerical model x_q is constant and equal for Region 1 and 2, and thus $dq_i/dw = 0$.

from Region 2 are higher, the absolute emissions increases are larger for lower tax rates. Moreover, the upstream subsidy always reduces emissions abroad. The effect is significant; emissions are reduced by around 15%.Note that even if we increase $m+n$ to 20, there is still a positive leakage from the downstream subsidy.

Finally, we have looked at the welfare of Region 2. Technology policy need not be a beggar-thy-neighbour policy in the case of emissions leakages. For all configurations except 1-3, Region 2 also enjoys higher welfare even if Region 1 only maximizes its own welfare.

6 Sensitivity to market structure

We have assumed Cournot competition upstream and perfect competition downstream. Although we think that imperfect competition with capacity constraints best describes the relevant upstream markets, Bertrand competition may also be possible upstream. We then know from Eaton and Grossman (1986) that the strategic trade motive of the government is turned around, that is, the government would prefer to tax production of its upstream firm in order to induce a price increase from the foreign upstream firm. In our model this is not likely to be desirable. First, it would increase leakage since the foreign downstream industry would do less abatement. Second, it would reduce the use of abatement equipment at home, which due to imperfect competition is too low. This latter point is also present in Eaton and Grossman (1986) as a rational for *not* taxing production with Bertrand competition when there is domestic consumption of the good in question.

Furthermore, competition in the downstream industry may not be perfect. If there is Cournot competition both upstream and downstream, there is also a profit shifting motive downstream. Keeping all other factors constant, this would make the downstream subsidy more attractive since it commits the downstream industry to a higher output by reducing the marginal cost of the downstream industry. Moreover, because the upstream subsidy reduces the marginal costs of the foreign firm, it would have a negative strategic effect. The effect on emissions leakage would, however, be the same. Thus, if the strategic effects of the two types of subsidies more or less cancel each other out, an upstream subsidy may still be desirable since reducing emissions leakages increases domestic welfare.

Some of our results might be thought to hinge on the assumption of fixed downstream demand. We have therefore solved the numerical model for linear demand downstream, and most results go through; in particular, the result that the price of abatement technology increases in the downstream subsidy and decreases in the upstream subsidy remains.[11] One possible exception is the effect on foreign emissions of an upstream subsidy. With linear demand downstream, a certain emissions rebound effect can occur as costs fall and

[11] A short note covering this case can be obtained from the authors upon request. The derivations are much more involved, and we therefore chose to keep the more simple model in the paper.

total downstream production increases. However, this rebound effect almost never dominates the primary effect of lowering emissions. Our numerical simulations with linear demand and initial demand elasticity of -0.75 give the same qualitative conclusions as with fixed demand.

Finally, we could have perfect competition both upstream and downstream. Increased subsidies could for instance stimulate entry of new upstream suppliers, making the upstream market (more) competitive.[12] Again, we can show that all the qualitative results for strategic subsidies carry over as long as the upstream industry has increasing marginal costs.

7 Discussion and 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. In this paper, we have considered to what degree abatement technology subsidies should be used, and whether they should be implemented downstream or upstream (or both). We conclude that a more robust recommendation can be made for upstream subsidies than for downstream subsidies. This is particularly the case from a strategic point of view for one region, but also in the case of maximizing global welfare when emissions taxes differ across regions. The results are to a large extent driven by the fact 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 have ambiguous effects on emissions leakage.

As we have discussed at several places in the paper, we find the case in which a downstream subsidy increases the world market price of abatement, the most likely outcome. However, we cannot completely rule out cases in which a downstream subsidy decreases the world market price of abatement equipment. The two kind of subsidies would then both reduce emissions leakage. Still, as long as the regulator cannot know the price effect of a downstream subsidy for sure, upstream subsidies are more robust.

Both kinds of subsidies come with some disadvantages, for instance related to social costs of public funds (Laffont and Tirole 1994 and David and Sinclair-Desgagne 2010). Including the social cost of public funds would make subsidizing more costly, and hence, reduce the desirability of technology policies. Based on the numerical simulations, in which upstream subsidies must be constrained not to exceed marginal upstream costs, we, however, conjecture that upstream subsidies still would increase welfare.

In our model, the private cost of producing pollution abatement equipment is given, and only an upstream subsidy can reduce this cost. In the introduction to this paper we argued that the upstream subsidy could be interpreted as an R&D subsidy that through increased R&D reduced the pro-

[12] David et al. (2011) examines the effects of emission taxes on entry and exit of abatement suppliers.

duction cost of the upstream industry. In this case we could have that the downstream subsidy also led to reduced cost by making private R&D more profitable at the margin. Would this change our results? That would depend on the strength of the induced R&D effect. The upstream firms would still increase their mark-up as a response to the downstream subsidy, and as long as this increase is larger than the reduction in production cost induced by the downstream subsidy, our results would not change. This is of course hard to know, and hence, in our opinion an upstream subsidy is more robust since limited use of it will for sure lead to lower prices on pollution abatement equipment.[13]

One may speculate whether upstream subsidies are more or less compatible with GATT law than downstream subsidies. On the one hand, countries could argue that they have chosen upstream subsidies over downstream subsidies since such subsidies will more likely reduce emissions both at home and abroad. On the other hand, Cosbey and Mavroidis (2014) argue that the WTO Agreement as it now stands does not consider environmental benefits as rationales for subsidies. Since both the downstream and the upstream subsidies involve financial contributions by the state to specific domestic recipients, they can in theory both be classified as domestic subsidies, which may be challenged under the WTO Agreement on Subsidies and Countervailing Measures. Nor does recent WTO case law offer clear guidance with respect to environmentally oriented subsidies; the Panel and Appellate Body in the Ontario Renewable Energy ruled against a local content requirement for the Ontario feed-in tariff (FIT), but could not agree on a finding that a feed-in tariff aimed at creating a new market, as distinct from conventional generation, should be equated to a subsidy (Cosbey and Mavroidis 2014; Charnovitz and Fischer 2015).

Charnovitz (2014) argues that the WTO rules lack clarity with respect to the use of green subsidies, and hence, that governments are uncertain to the extent they are WTO legal. A potential danger with upstream subsidies is thus that the region receiving the increased export of pollution abatement equipment enacts countervailing duties. The reduction in emission leakage from increased use of abatement equipment in that region might then not occur.

One issue we haven't discussed so far is distributional impacts within the region. The upstream subsidy directly supports an industry that already is profiting from market power, and indirectly supports a pollutive industry through lower prices of abatement equipment. The downstream subsidy also supports both industries directly or indirectly. These effects could be considered undesirable by other stakeholders in the region, who may stand to lose due to increased taxation or reduced government spending.

We have only analyzed unilateral technology policy, and it would clearly

[13] Interested readers should check out an earlier version of this paper in which we include R&D by upstream firms, and show, for a particular R&D function, that our main results still hold, see Fischer et al (2012).

be interesting to look at a Nash-equilibrium in technology policies. For $\eta_1 = \gamma_1 = 0$, Region 2 would have the same incentives as Region 1, and there might exist a Nash-equilibrium with positive upstream subsidies in both regions. If regions are similar, they might both benefit from this due to the increased use of abatement technology in both regions (see end of the numerical section above). Thus, as opposed to strategic trade policy, subsidizing production of abatement technology may not qualify as a Prisoners Dilemma.

We have also treated the emissions tax rates as exogenous. In case the emissions in question comes from many sources, such as greenhouse gases, the emissions tax rates will not be decided with regards to the industry in our model alone. On the contrary, technology policy can be tailor-made to separate industries and their abatement technology needs. In case emissions are special for the industry we are looking at, it would be interesting to make emissions taxes endogenous. If one believes that governments can adjust technology policy more easily than emissions taxes, one may also assume that taxes are set before technology policy. Do regions then set the tax high because they know that this commits them to a tough technology policy, or do regions set the tax low in order to make regions commit to a tough technology policy from which they also will benefit? This might be an interesting avenue of future research.

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, which is used in the EU Emission Trading System? Output-based allocation of emission quotas work in very much the same way as a combination of an emission price and an output subsidy, which will tend to increase downstream demand for cleaner technology, compared to emission pricing only. Thus, output-based allocation will avoid some leakage from the emissions tax, by shifting less downstream production, but it will have only indirect effects on foreign industries' abatement technology choices, and will not give local upstream abatement technology firms a relative advantage. Thus, the most robust policy for reducing emissions leakage remains the upstream subsidy, which encourages global adoption of cleaner technologies.

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A Downstream equilibrium

Differentiating the four first-order conditions (3) and (4), and keeping Q constant:

$$\begin{aligned}
0 &= e_{1xx}dx_1 + e_{1xq}dq_1 - d\theta_1 \\
0 &= e_{2xx}dx_2 + e_{2xq}dq_2 - d\theta_2 \\
0 &= h_{1qq} + t_1\left(e_{1qq}dq_1 + e_{1qx}dx_1\right) + e_{1q}dt_1 - dP \\
0 &= h_{2qq} + t_2\left(e_{2qq}dq_2 + e_{2qx}dx_2\right) + e_{2q}dt_2 - dP \\
0 &= dq_1 + dq_2
\end{aligned}$$

Let $\chi = e_{1xx}e_{2xx}(h_{1qq}+h_{2qq}+e_{1qq}t_1+e_{2qq}t_2)-t_1(e_{1xq})^2e_{2xx}-t_2(e_{2xq})^2e_{1xx}$. We assume that demand is well-behaved and downward sloping in our region of interest, and the direct effects dominate the indirect ones, so $\chi > 0$.

Solving for the downstream output changes we then obtain:

$$\frac{dq_1}{d\eta_1} = \frac{e_{1xq}e_{2xq}}{\chi} > 0$$
$$\frac{dq_1}{dt_1} = \frac{e_{1xq}\theta_1 - e_{2xx}e_{1xx}e_{1q}}{\chi} < 0$$
$$\frac{dq_1}{dw} = \frac{e^2_{xx}e^1_{xq}(1-\eta_1) - e^1_{xx}e^2_{xq}(1-\eta_2)}{\chi}$$

Note that $dq_2/d\eta_1 = -dq_1/d\eta_1$ etc. The derivative dq_1/dw can be rewritten by using $dx_i/dq_i = -e_{ixq}/e_{ixx}$:

$$\frac{dq_1}{dw} = [(1-\eta_2)x_{2q} - (1-\eta_1)x_{1q}]\frac{e_{1xx}e_{2xx}}{\chi}$$

In general we cannot sign $\partial q_i/\partial w$. However, for $\eta_1 = \eta_2$ and $t_1 > t_2$, we will assume $x_{2q}(q_2,\theta_2) \le x_{1q}(q_1,\theta_1)$, and hence $\partial q_2/\partial w \ge 0 \ge \partial q_1/\partial w$.

B The elasticity of abatement demand

First, we have for η_1:

$$\frac{dY}{d\eta_1} = [x_{1q} - x_{2q}]\frac{dq_1}{d\eta_1} - x_{1\theta}\frac{w}{t_1} > 0$$

since $x_{1\theta} < 0$, and since we assume $\Delta = [x_{1q} - x_{2q}]\frac{dq_1}{dw} \approx 0$, we accordingly assume $[x_{1q} - x_{2q}]\frac{dq_1}{d\eta_1} \approx 0$. Next we have:

$$\frac{d^2Y}{d\eta_1 dw} = d\left\{-x_{1\theta}\frac{w}{t_1}\right\}/dw_1$$
$$= \frac{-x_{1\theta}}{t_1} - x_{1\theta\theta}\frac{(1-\eta_1)w}{(t_1)^2} - x_{1\theta q}\frac{w}{t_1}\frac{dq_1}{dw}$$

$[x_{1q} - x_{2q}]\frac{dq_1}{d\eta_1} \approx 0$, implies x_{iq} close to constant. Thus, $x_{i\theta q} \approx 0$. Note that $x_{1q\theta}$ is exactly zero if the cross derivatives e_{ixxq}, e_{ixq} are zero. Moreover, we have:

$$sign\,[x_{1\theta\theta}] = \theta_1 e_{1xxx} - e_{1xx}$$

We assume $\theta_1 e_{1xxx} - e_{1xx} \le 0$. Thus, given our assumptions $\frac{d^2Y}{d\eta_1 dw} > 0$. We then have:

$$\frac{d\,|El_{Y,w}|}{d\eta_1} = \left(-\frac{1}{Y}\frac{dY}{d\eta_1}\left|\frac{dY}{dw}\right| + \frac{d\left|\frac{dY}{dw}\right|}{d\eta_1}\right)\frac{w}{Y} < 0$$

since $d\left|\frac{dY}{dw}\right|/d\eta_1 < 0$ when $d^2Y/d\eta_1 dw > 0$.

C Comparative statics of the upstream equilibrium

The upstream subsidy has direct effects on supply and indirect effects on supply and demand through the equipment price. From 6 and 8,

$$Y^S = \frac{2(w-\rho)+(\gamma_1+\gamma_2)\rho}{s} = x\left(q_1(t_1,\theta_1,t_2,\theta_2),\theta_1\right)+x\left(q_2(t_1,\theta_1,t_2,\theta_2),\theta_2\right) = Y^D$$

Totally differentiating,

$$\frac{\rho}{s}d\gamma_i + \frac{2}{s}dw - \frac{Y^S}{s}ds = \frac{dY^D}{dw}dw = \frac{-dw}{s}$$

Simplifying and rearranging, we get $\rho d\gamma_i + 3dw - Y ds = 0$, from which we derive the price change as a function of the change in the upstream subsidy in country i:

$$\frac{dw}{d\gamma_i} = -\frac{\rho}{3-\frac{ds}{dw}Y} < 0$$

where $\frac{ds}{dw} = s^2\frac{d^2Y^D}{dw^2}$. From the assumption of strategic substitutes, $\frac{ds}{dw}y_i < 1$ implies $\frac{ds}{dw}Y < 2 < 3$.

From 8, we differentiate and obtain the change in total supply:

$$\begin{aligned}\frac{dY}{d\gamma_i} &= \frac{\rho}{s} + \frac{1}{s}\left(2 - Y\frac{ds}{dw}\right)\frac{dw}{d\gamma_i}\\ &= \frac{\rho}{s}\left(1-\left(\frac{2-Y\frac{ds}{dw}}{3-Y\frac{ds}{dw}}\right)\right) > 0\end{aligned}$$

The upstream subsidy shifts out the supply curve and, with downward-sloping demand, drives down the global price of equipment, increasing the total quantity traded.

From 7, we solve for the individual upstream production quantities:

$$y_i = \frac{w-(1-\gamma_i)\rho}{s}$$

The response of the domestic and foreign firm to an increase in γ_1 is

$$\begin{aligned}\frac{dy_1}{d\gamma_1} &= \frac{\rho}{s} + \frac{1}{s}\left(1 - y_1\frac{ds}{dw}\right)\frac{dw}{d\gamma_i}\\ &= \frac{\rho}{s}\left(1-\left(\frac{1-y_1\frac{ds}{dw}}{3-Y\frac{ds}{dw}}\right)\right) > 0;\\ \frac{dy_2}{d\gamma_1} &= \frac{1}{s}\left(1 - y_2\frac{ds}{dw}\right)\frac{dw}{d\gamma_i}\\ &= -\frac{\rho}{s}\left(\frac{1-y_2\frac{ds}{dw}}{3-Y\frac{ds}{dw}}\right) < 0.\end{aligned}$$

The effect of a downstream subsidy or emissions tax is to increase total abatement demand and thus w, inducing both upstream firms to increase their supply:

$$\frac{dy_1}{dw} = \frac{1}{s}\left(1 - y_1\frac{ds}{dw}\right) > 0;$$
$$\frac{dy_2}{dw} = \frac{1}{s}\left(1 - y_2\frac{ds}{dw}\right) > 0.$$

D Comparative statics of the downstream equilibrium

We now let w be endogenously determined, that is, $\partial w/\partial \eta_1, \partial w/\partial t_1, \partial w/\partial \gamma_i \neq 0$.We still have $dq_1 = -dq_2$. Moreover, we maintain the assumption that the marginal effects of output on abatement demand Δ is dominated by the direct effect of a downstream subsidy/emission tax increase. This implies that:

$$\begin{aligned}
\frac{dq_1}{d\eta_1} &= \frac{dq_1}{d\eta_1}|_w + \frac{dq_1}{dw}\frac{dw}{d\eta_1} \\
&= \frac{e_{1xq}e_{2xq}}{\chi} + [(1-\eta_2)x_{2q} - (1-\eta_1)x_{1q}]\,\frac{e_{1xx}e_{2xx}}{\chi}\frac{dw}{d\eta_1} \\
&\approx \frac{e_{1xq}e_{2xq}}{\chi} > 0 \\
\frac{dq_2}{d\eta_1} &= -\frac{dq_1}{d\eta_1} < 0
\end{aligned}$$

where $\chi = e_{1xx}e_{2xx}(h_{1qq}+h_{2qq}+e_{1qq}t_1+e_{2qq}t_2)-t_1(e_{1xq})^2e_{2xx}-t_2(e_{2xq})^2e_{1xx} > 0$.

The sign on dq_i/dw is discussed in Appendix A.

Further, for the effect of an increase in the tax rate, we have:

$$\begin{aligned}
\frac{dq_1}{dt_1} &= \frac{dq_1}{dt_1}|_w + \frac{dq_1}{dw}\frac{dw}{dt_1} \approx \frac{e_{1xq}\theta_1 - e_{2xx}e_{1xx}e_{1q}}{\chi} < 0 \\
\frac{dq_2}{dt_1} &= -\frac{dq_1}{dt_1} > 0
\end{aligned}$$

To derive the effect on the downstream market price, first let's add the two price identities, so $2P = h'(q_1) + h'(q_2) + t_1e_{1q} + t_2e_{2q}$. Differentiating the downstream product price with respect to η_1:

$$\begin{aligned}
2\frac{dP}{d\eta_1} &= -we_{1qx}x_{1\theta} + ((1-\eta_1)e_{1qx}x_{1\theta} + (1-\eta_2)e_{2qx}x_{2\theta})\,\frac{dw}{d\eta_1} \\
&\quad + \left(h_1'' + t_1e_{1qq} - h_2'' - t_2e_{2qq}\right)\frac{dq_1}{d\eta_1}
\end{aligned}$$

The first term is negative due to the direct effect of the subsidy. The second term is positive since $e_{1qx} < 0$, $x_{1\theta} < 0$ and $dw/d\eta_1 > 0$. The third term is a second order effect from a reallocation of output. It may be zero or negative since a change in output is likely to increase marginal cost less for the producer with the lowest output e.g. $q_1 < q_2$ for $t_1 > t_2$. Anyhow, since it is a second order effect, we assume it is dominated by the two other terms.

The effect of the upstream subsidy γ_i on the downstream price is more straightforward, since $dw/d\gamma_i < 0$, although the price-depressing effect may be attenuated or enhanced by differences in carbon pricing:

$$
\begin{aligned}
2\frac{dP}{d\gamma_i} &= ((1-\eta_1)e_{1qx}x_{1\theta} + (1-\eta_2)e_{2qx}x_{2\theta})\,\frac{dw}{d\gamma_1} \\
&\quad + \left(h_1'' + t_1 e_{1qq} - h_2'' - t_2 e_{2qq}\right)\frac{dq_1}{dw}\frac{dw}{d\gamma_1}
\end{aligned}
$$

The first term is negative since both downstream industries increases their use of abatement equipment which makes the emission tax payments from an output expansion less costly, and marginal production cost is lowered. For the second order effect we conjecture, as above, that it is zero or negative, and thus, $dP/d\gamma_i < 0$. Anyhow, since it is a second order effect, we assume it is dominated by the other term.

Note that if abatement is independent of production ($x_q = 0$), the downstream price is independent of abatement technology subsidies.

E The numerical example

We describe a stylized downstream industry inspired by Laffont and Tirole (1996). Let there be S firms in each region, each with unit production. With $S > Q$, each region could in theory serve the entire global market; however, production costs among the firms are heterogeneous, leading to upward-sloping supply curves in each region. Let the cost of a firm be uniformly distributed on $[0, S]$, reflecting different degrees of efficiency of input use, such as may arise from different capital vintages. Denote by $q_i \in [0, Q]$ the number of firms producing (= production); then the sum of production costs c_i for the regional industry as a whole is quadratic: $h(q_i) = q_i^2/2$.

Gross emissions from each firm are assumed to be proportional to costs; in other words, firms with high costs use inputs—like energy—inefficiently and thus also have high emissions. Let regional gross emissions thus be $e_i = (q_i)^2/2$. However, an abatement technology exists that reduces emissions, independent of the vintage, down to that of the best performer (in this case 1/2, the emissions of the first firm in the distribution). Given the cost of installation, the most polluting lines will install abatement technology first. Denote by x_i the number of firms that install the abatement technology in region i; emissions from these firms will then be $x_i/2$. The firms not installing the abatement technology will be distributed on $[0, (q_i - x_i)]$, and their emissions will total $(q_i - x_i)^2/2$. Thus, regional net emissions are $e_i = ((q_i - x_i)^2 + x_i)/2$.

Downstream firms are perfectly competitive, and their abatement decisions are made to minimize their compliance costs: emissions tax payments $t_i e_i$ plus technology costs $(w - \eta_i)x_i$ (in the example we use a fixed per unit downstream subsidy). For the firm in region i that is just indifferent to adopting the abatement technology, we have $t_i(q_i - x_i - 1/2) = t_i/2 + w - \eta_i$ (The incremental emissions of the last non-adopter are $\int_{q_i - x_i - 1}^{q_i - x_i} z dz = q_i - x_i - 1/2$), or

$$x_i = q_i - \frac{w - \eta_i}{t_i} - 1 \tag{21}$$

Thus, the equilibrium level of emissions is

$$\varepsilon_i = \frac{1}{2}\left(\left(\frac{t_i + w - \eta_i}{t_i}\right)^2 + q_i - \frac{t_i + w - \eta_i}{t_i}\right) = \frac{1}{2}\left(q_i + \frac{(w - \eta_i)(t_i + w - \eta_i)}{t_i^2}\right) \tag{22}$$

and total costs of regional supply, C_i, inclusive of not only production costs c_i but also emissions payments and abatement equipment purchases, are

$$C_i = \frac{q_i^2}{2} + t_i e_i + (w - \eta_i)x_i$$

Substituting the expressions from (21) and (22), we can write this cost function in reduced form as

$$C_i = \frac{q_i^2}{2} + \left[\frac{t_i}{2} + w - \eta_i\right] q_i + f_i \tag{23}$$

where $f_i = -(w - \eta_i)(t_i + w - \eta_i)/(2t_i)$. From (23) we note that the supply curve of each industry is upward sloping and linear. Furthermore, a higher regional tax shifts the supply curve vertically upwards, while a regional abatement subsidy shifts the curve vertically downwards.

In equilibrium the marginal cost of the two industries must be equal to the downstream price P; that is, $P = q_1 + t_1/2 + w - \eta_1$ and $P = q_2 + t_2/2 + w - \eta_2$. Adding these two regional price equations, and using the fact that global supply must equal global demand ($q_1 + q_2 = Q$), we find the reduced form for the downstream market price is given by:

$$P = \frac{Q + (t_2 + t_1)/2 + 2w - \eta_1 - \eta_2}{2}$$

Substituting, we derive the equilibrium supply of the industry in region i:

$$q_i = \frac{Q + (t_j - t_i)/2 + \eta_i - \eta_j}{2}. \tag{24}$$

E.1 The upstream market equilibrium

Global demand for abatement technology is the sum of the two regional demands, i.e., $x_1 + x_2$. Using (21) and (24), and inverting the resulting abatement technology demand function, we obtain the inverse demand curve for the upstream suppliers:

$$w = \frac{t_1 t_2}{t_1 + t_2}\left(Q + \frac{\eta_1}{t_1} + \frac{\eta_2}{t_2} - 2 - x_1 - x_2\right)$$

In equilibrium $my_1 + ny_2 = x_1 + x_2$. All firms maximize profits: $[w - \rho + \gamma_i]\, y_i$. The Nash-equilibrium outputs and price of abatement technology are then given by:

$$y_1 = \frac{1}{m+n+1}\left[Q - 2 + \frac{\eta_1}{t_1} + \frac{\eta_2}{t_2} - \frac{t_1 + t_2}{t_1 t_2}\left[\rho - (n+1)\gamma_1 + n\gamma_2\right]\right]$$
$$y_2 = \frac{1}{m+n+1}\left[Q - 2 + \frac{\eta_1}{t_1} + \frac{\eta_2}{t_2} - \frac{t_1 + t_2}{t_1 t_2}\left[\rho + m\gamma_1 - (m+1)\gamma_2\right]\right]$$

For the total supply of abatement equipment we have:

$$x_1 + x_2 = \frac{m+n}{m+n+1}\left[Q - 2 + \frac{\eta_1}{t_1} + \frac{\eta_2}{t_2}\right] - \frac{t_1 + t_2}{t_1 t_2}\frac{(m+n)\rho - m\gamma_1 - n\gamma_2}{m+n+1}$$

from which we obtain the upstream price:

$$w = \frac{t_1 t_2}{(t_1 + t_2)(m+n+1)}\left[Q - 2 + \frac{\eta_1}{t_1} + \frac{\eta_2}{t_2}\right] + \frac{(m+n)\rho - m\gamma_1 - n\gamma_2}{m+n+1}$$

It is now easy to simulate the model. In our baseline example, we let $Q = 100$, $\mu = 0.5$, $m + n = 4$, $t_1 = t_2 = 1$ and both types of subsidies in both regions are initially zero. The value of ρ is calibrated so that $x_i = 25$; i.e., half of the firms in each region buy abatement equipment, given the emissions tax (this gives $\rho = 18$). We then introduce optimal subsides in Region 1 while keeping $\eta_2 = \gamma_2 = 0$.