



UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

WORKING PAPERS IN ECONOMICS

No 626

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by

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September 2015

ISSN 1403-2473 (print)

ISSN 1403-2465 (online)

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September 7, 2015

Abstract

We analyze the interplay between policies aimed to control global and local pollution such as greenhouse gases and particulate matter. The two types of pollution interact in the abatement cost function of the polluting firms through economies or diseconomies of scope. They are regulated by distinct entities (global versus local), potentially with different instruments that are designed according to some specific agenda. We show that the choice of regulatory instrument and the timing of the regulations matter for efficiency. Emissions of local pollution are distorted if the local regulators anticipate that global pollution will later be regulated through emission caps. The regulation is too (not enough) stringent when abatement efforts exhibit economies (diseconomies) of scope. In contrast, we obtain efficiency if the global pollutant is regulated by tax provided that the revenues from taxing emissions are redistributed to the local communities in a lump-sum way.

Key Words: environmental regulation, multiple-pollutants, policy spillovers, emission tax, emission standard, emissions trading.

JEL classification: D62, Q50, Q53, Q54, Q58.

*Research funding from the Swedish Foundation for Humanities and Social Sciences (Riksbankens Jubileumsfond) and the French National Research Agency through the project ANR-12-BSH1-0003-01 on "Political Economy of the Environment" is gratefully acknowledged. We thank Wolfgang Habla for useful comments and suggestions.

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1 Introduction

Many local air pollutants and greenhouse gases (GHG) have common sources. For example, passenger vehicles and coal power plants emit nitrogen oxides (NO_x) and carbon dioxide (CO_2), which affect the local air quality and the climate. Hence, regulations directed at local air pollutants affect GHG and vice versa. Situations in which a policy aimed at one pollutant affects emissions of another are referred to as *policy spillovers*. These spillovers can lead to ancillary benefits if they act in the same positive direction for the environment. For instance, climate policies that cause energy efficiency improvements might lead to less fossil fuel combustion and lower emissions of local air pollutants. However, there are also examples of climate mitigation measures that can lead to increased emissions of other pollutants. For example, greater use of biomass in combustion sources may reduce GHG emissions but could increase emissions of NO_x and particulate matter (PM_{10}) (see Pittel and Rübhelke 2008 for a survey).

Policy spillovers clearly have implications for policy design and cost-benefit analysis, as they affect both the effectiveness and cost of specific policy measures; failure to account for them increases the cost of meeting a particular environmental objective, making it less acceptable to policymakers and to the public. This concern is readily apparent in the case of China: climate change, largely ignored as a problem in the past, has suddenly become a high national priority since the Chinese government is realizing the opportunities to achieve climate mitigation through integration of GHG emissions reductions into reductions of local pollution (Teng and Gu 2007, Qi et al. 2008). In November 2014, China publicly pledged to peak GHG emission by 2030 and then remain steady or begin reduce the levels. China's position in the international arena stems from a recognition of the need to reduce the country's coal dependency, due to domestic pollution. The country has boosted its investment in wind power, the capacity of which now exceeds that of nuclear power. Green and Stern (2015) estimate that GHG emissions in China are likely to peak by 2025, and could well peak earlier.

The spillover effect of local pollution abatement on GHG emissions seems to be good news for the climate. Yet it is not always the case. First, the spillovers might be negative in the sense that reducing local pollution might increase (and not decrease) the cost of mitigating GHG emissions. For instance, if instead of moving to renewable sources of energy China installs more buffers on thermal power plants, more energy is used, leading to higher CO_2 emissions. Second, the spillover effect might provide perverse incentives for guiding local environmental policy. A country might strategically choose its local regulation to be in a better position in an international deal on GHG emissions. In particular, a country might want to modify the cost of abating GHG emissions through its choice of local regulation in order to obtain a less stringent emission cap in a Kyoto-style agreement. Therefore, it is crucial to understand how policies can be designed such that local pollution is reduced and global climate mitigation efforts enhanced.

In this paper we analyze the interplay between climate and local pollution regulations in the pres-

ence of policy spillovers. In particular, we analyze the question of how the choice of policy instrument affects the stringency of the policies and its efficiency. In our study, we assume that in each country there is a polluting firm that causes transboundary and local pollution. Pollution abatement levels for both pollutants interact in the abatement cost function of firms through economies/diseconomies of scope. As a local regulator, a country's objective is to minimize the sum of the damage and the abatement costs of the local pollutant, whereas the global regulator is charged with maximizing aggregate welfare. Each regulator influences the behavior of the polluter with respect to pollution abatement by means of a variety of regulatory instruments (e.g., cost-efficient non-tradable quotas and taxes). These regulations can be designed either simultaneously or sequentially. In such a setting, each regulator's policy has the potential to affect the other regulator's welfare. However, as we show in the paper, whether or not that happens depends on the type of policies chosen by the regulators.

To the best of our knowledge, this is the first study that analyzes the effects of the choice of policy instruments under policy spillovers and regulation of multiple pollutants. Our paper relates to various literatures. For example, it builds on the literature on regulation of multiple pollutants when those pollutants interact in abatement costs or environmental damages (see, e.g., Moslener and Requate 2007, Burtraw et al. 2012, Ambec and Coria 2013, Fullerton and Karney 2014, Antoniou and Kyriakopoulou 2015, and Stanlund and Son 2015). Most of such literature compares the efficiency of several instruments designed by one regulator who is in charge of the two pollutants or only one (the regulation of the other pollutant being exogenous). In contrast, we deal with two regulators, each of them in charge of a different pollutant since our focus is on policy spillovers. Hence, we are able to characterize the additional sources of inefficiency that might arise due to multigovernance of pollution control.

Our paper also relates to the literature on environmental federalism, which attempts to find the socially optimal assignment of environmental policy to the different tiers of government. Centralized decision-making can better exploit economies of scale in the provision of public goods, and can better internalize spillovers across local jurisdictions (e.g., Williams 1966, Oates and Schwab 1988, Gordon 1983, Williams III 2012). In such literature, researchers consider only one pollutant that diffuses imperfectly across states. In contrast, our analysis considers two pollutants: one local and one global. Our focus is not on what level of government should optimally regulate pollution, but on the interplay between regulation of local pollution at the state or country level and regulation of global pollution at the federal or international level.

Our paper also contributes to the literature on countries' strategies under the expectation of future climate agreements.¹ For instance, Beccherle and Tirole (2011) show that delaying binding climate

¹Previous studies have also analyzed the strategic implications of policy spillovers for participation in international climate agreements (see, e.g., Finus and Rübbecke 2013). They find that in the presence of ancillary benefits, the relative importance of an international agreement for climate protection is reduced since ancillary benefits already

change agreements will induce countries not only to engage in suboptimal efforts to reduce their current emissions but also to commit to higher pollution levels post-negotiations. In the same vein, Harstad (2015) points out that future climate negotiations hold up countries' investments in R&D related to GHG abatement technologies, thereby leading to underinvestment. Our paper identifies further inefficiencies due to countries' strategic behavior when a future climate agreement is expected: the ones related to local air pollution. They arise when a global target for GHG reduction is implemented through cost-efficient abatement quotas: countries distort the stringency of local pollution regulation to obtain lower abatement obligations in the future climate agreement. The departure from first-best regulation depends on the economies or diseconomies of scope parameter; countries under-abate (over-abate) local air pollution when there are economies (diseconomies) of scope between abatement on global and local pollution in order to increase the marginal cost of abating the global pollutant and thus to reduce the abatement quota. Such a strategic manipulation of local environmental policy does not arise when the GHG reduction is implemented through emission taxes provided that the tax is collected and redistributed to countries by an international organization in a lump-sum way. When the tax on emissions is levied and kept by the country, we end up with the same distortion on local air pollution as with quotas. In such case, a country does not internalize the impact of its choice of regulation stringency on global welfare through abatement costs. This result goes against Weitzman's (2014) argument that taxing emissions to resolve the global warming problem is better than a cap-and-trade system because a country has a self-interest in collecting taxes. In our framework with policy spillovers between local and global air pollution, the first-best outcome can be reached with cap-and-trade but not with a tax if countries are assigned the revenue from taxing global pollution in a non-lump-sum way.

Finally, our paper is also related to the literature on common agency and coordination.² A basic assumption of this literature is that the various regulatory agencies are only able to contract in their own sphere of responsibilities. As a result, the regulation implemented is a Nash or Stackelberg equilibrium among various regulations offered in a decentralized way. Under this complex structure, the regulatory process introduces allocative inefficiencies since an individual regulator does not take other regulations into account when designing his own regulation. Within this literature, the closest paper to ours is Baron (1985). He analyzes a model where the Environmental Protection Agency, acting as a Stackelberg leader, regulates pollution, and a public utility commission regulates the price for a monopolist that has private information about the effectiveness of its abatement alternatives. In the resulting noncooperative equilibrium, pollution control is carried beyond the first best and output is too low. Efficiency improvements in this setting would arise from direct cooperation between the

provide incentives for protection in a non-cooperative setting.

²Common agency games with complete information were introduced by Bernheim and Whinston (1996). See Martimort (1996) for a review of the literature.

EPA and the commission, from Coasian bargaining between them, or from an authority with the power to impose a policy that balances consumer, pollutee, and producer interests. In line with Baron's (1985) results, we find that when the global regulator is charged with maximizing aggregate welfare, optimality is achieved regardless of the choice of policy instruments either when both regulators move simultaneously or the global regulator moves first. Hence, our results indicate that timing only matters when the global regulation is implemented through quotas. In such case, simultaneous regulation leads to first best while the outcomes of sequential regulation depend on who moves first. In particular, if the local regulator moves first, the outcome is inefficient: countries will under-abate or over-abate local pollution and there will be too little abatement of the global pollutant.

This paper is organized as follows. Section 2 introduces the model. It also characterizes pollution abatements for both pollutants absent any international obligation on global pollution and the first-best outcome for a given target on global pollution. Section 3 analyses the impact of several policy instruments on pollution: abatement quotas (or emission caps), emission taxes, and tradable emission allowances. Section 4 investigates the robustness of our results to the existence of a dominant country that has a large impact on global pollution. Section 5 concludes the paper.

2 Model

2.1 Main assumptions

We have a continuum of countries (or local regulators). In each country there is a polluting firm that causes transboundary and local pollution. Firms can jointly reduce the local pollutant (denoted pollutant 1) and the global pollutant (denoted pollutant 2). The total cost of reducing emissions is denoted $C(q_1, q_2, \omega)$, where q_i denotes pollution abatement in pollutant i for $i = 1, 2$. We have that $C(q_1, q_2, \omega)$ is increasing and convex in both arguments: $C_i > 0$ and $C_{ii} > 0 \forall i = 1, 2$ where C_i and C_{ii} denote the first and second derivatives with respect to q_i . We assume the following quadratic and symmetric functional form:

$$C(q_1, q_2, \omega) = \frac{mq_1^2}{2} + \frac{mq_2^2}{2} + \omega q_1 q_2.$$

The parameter ω measures the degree to which there are economies or diseconomies of scope in joint abatement in each country. Formally, there are economies of scope if $C(q_1, q_2, \omega) < C(q_1, 0, \omega) + C(0, q_2, \omega)$, which happens with our functional form if and only if $\omega < 0$. There are diseconomies of scope if the reverse holds. We refer to economies (diseconomies) of scope as complementarity (substitutability). Hence, if $\omega < 0$ ($\omega > 0$), the two pollutants are complements (substitutes) in the cost function in the sense that reducing emissions of one pollutant decreases (increases) the total (and marginal) cost of reducing emissions of the other. The spillover parameter ω is distributed in the range $\Omega \equiv [\underline{\omega}, \bar{\omega}]$ according to a probability density $f(\omega)$ and cumulative $F(\omega)$ where $dF(\omega) = f(\omega)d\omega$, and

$f(\omega) > 0$ for every $\omega \in \Omega$. Moreover, we assume $m > 0$, $m^2 - \omega^2 > 0$ to ensure increasing and strictly convex marginal costs.³

Let a country' benefit from reducing emissions be denoted

$$B(q_1(\omega), Q_2) = a_1 q_1(\omega) - \frac{b_1}{2} [q_1(\omega)]^2 + a_2 Q_2 - \frac{b_2}{2} [Q_2]^2,$$

where Q_2 is the aggregate level of abatement of pollutant 2:

$$Q_2 = \int_{\underline{\omega}}^{\bar{\omega}} q_2(\omega) dF(\omega). \quad (1)$$

We assume that $B(q_1(\omega), Q_2)$ is increasing and concave in its main arguments, i.e., $B_i > 0$ and $B_{ii} \leq 0$ for $i = 1, 2$. Countries differ only in the interaction parameter ω in the cost function.

Before examining regulatory instruments, let us analyze pollution abatement in two cases: without any international agreement or regulation on global pollution and under the cost-efficient solution for a given global abatement target.

2.2 Pollution abatement without international regulation of global pollution

In the absence of any commitment at the international level for pollutant 2, each country ω chooses the abatement levels $q_1(\omega)$ and $q_2(\omega)$ that maximize own welfare $B(q_1(\omega), Q_2) - C(q_1(\omega), q_2(\omega), \omega)$ subject to the non-negativity constraints on abatement $q_i(\omega) \geq 0$ for $i = 1, 2$ with Q_2 defined in (1). With λ_i^e denoting the Lagrangian multiplier associated with the non-negative constraint on $q_i(\omega)$ for $i = 1, 2$, we obtain the following first-order conditions:

$$\begin{aligned} B_1(q_1^e(\omega), Q_2^e) &= C_1(q_1^e(\omega), q_2^e(\omega), \omega) - \lambda_1^e, \\ B_2(q_1^e(\omega), Q_2^e) \frac{dQ_2}{dq_2(\omega)} &= C_2(q_1^e(\omega), q_2^e(\omega), \omega) - \lambda_2^e, \end{aligned}$$

plus the complementary slackness conditions derived from the two non-negativity constraints. First, we have $\frac{dQ_2}{dq_2(\omega)} = 0$ because a country's abatement has a negligible impact on the aggregate abatement of the global pollutant Q_2 . Second, our assumptions ensure an interior solution for local abatement: $q_1^e(\omega) > 0$ for every $\omega \in \Omega$ and therefore $\lambda_1^e = 0$. Hence, with our functional forms, the first-order conditions become:

$$a_1 - b_1 q_1^e(\omega) = m q_1^e(\omega) + \omega q_2^e(\omega), \quad (2)$$

$$0 = m q_2^e(\omega) + \omega q_1^e(\omega) - \lambda_2^e. \quad (3)$$

³That is, $C_i(q_1, q_2, \omega) > 0$, $C_{ii}(q_1, q_2, \omega) > 0$, and $C_{ii}C_{jj} - C_{ij}^2 > 0$ for any $q_i \in [0, e_i^e]$ for $i, j = 1, 2$ and $i \neq j$, where e_i^e is the uncontrolled level of emissions. Similar assumptions on the cost function are used by Stranlund and Son (2015), Ambec and Coria (2013), Burtraw et al. (2012), and Moslener and Requate (2007), who study the optimal regulation of multiple pollutants. These assumptions imply that the second-order conditions of the maximization programs hold.

A country equalizes the marginal benefit of abating each pollutant to its marginal cost, which depends on both pollutants through the interaction parameter ω . The marginal cost is net of λ_2^e (which is the implicit cost of the non-negativity constraint for the global pollutant). Therefore, even if the marginal benefit of abating the global pollutant is zero, a country might want to reduce global pollution because it reduces the cost of abating local pollution. However, this turns out to be the case if and only if $\omega < 0$, i.e., under economics of scope in abatement. Indeed, if $\lambda_2^e > 0$, then $q_2^e(\omega) = 0$ and (3) becomes $\omega q_1^e(\omega) = \lambda_2^e$ which is compatible with $q_1^e(\omega) > 0$ if and only if $\omega > 0$. In this case, we know by equation (2) that abatement of local pollution is:

$$q_1^e(\omega) = \frac{a_1}{b_1 + m}.$$

In contrast, when $\omega < 0$, we have $\lambda_2 = 0$ and thus (3) becomes $q_2^e(\omega) = -\frac{\omega}{m} q_1^e(\omega)$, which, combined with (2), leads to:

$$q_1^e(\omega) = \frac{a_1 m}{m b_1 + m^2 - \omega^2}, \quad (4)$$

and

$$q_2^e(\omega) = \frac{-a_1 \omega}{m b_1 + m^2 - \omega^2}. \quad (5)$$

Therefore, total abatement of global pollution in the absence of any international agreement on global pollution is:

$$Q_2^e = \int_{\underline{\omega}}^0 q_2^e(\omega) dF(\omega) = \int_{\underline{\omega}}^0 \frac{-a_1 \omega}{m b_1 + m^2 - \omega^2} dF(\omega).$$

This is to say, even in the absence of a regulation on global pollution there will be some positive level of abatement since countries for which local and global abatement are complements freely choose to abate global pollution only because it reduces the cost of abating local pollution. Empirical studies have shown that the existence of ancillary benefits of climate change mitigation might lead to significant reductions of global pollution. For instance, Parry et al. (2014) estimate that the existence of ancillary benefits of climate mitigation should lead the top 20 emitters to unilaterally (and without a need to wait for global regulations) reduce their GHG emissions by 13.5 percent (which implies a 10.8 percent reduction in global emissions).

2.3 The regulated solution with an exogenous global pollution target

We examine cost-efficient abatement efforts for both pollutants for a given abatement target for global pollution \bar{Q}_2 . We refer to this target as first best even though the target \bar{Q}_2 is exogenous and therefore it may be inefficient (though it is endogenized later in Section 3.3). As shown later, \bar{Q}_2 is higher than the unregulated aggregate abatement Q_2^e .

Given \bar{Q}_2 , the optimal allocation of abatement efforts $\{q_1(\omega), q_2(\omega)\}_{\omega \in \Omega}$ maximizes the expected total welfare:

$$\int_{\underline{\omega}}^{\bar{\omega}} [B(q_1(\omega), \bar{Q}_2) - C(q_1(\omega), q_2(\omega), \omega)] dF(\omega),$$

subject to the non-negativity constraints $q_j(\omega) \geq 0$ for $j = 1, 2$ and the target constraint:

$$\int_{\underline{\omega}}^{\bar{\omega}} q_2(\omega) dF(\omega) \leq \bar{Q}_2.$$

The Langrangian of the above program is:

$$\mathcal{L} = \int_{\underline{\omega}}^{\bar{\omega}} [B(q_1(\omega), \bar{Q}_2) - C(q_1(\omega), q_2(\omega), \omega) + k^* [\bar{Q}_2 - q_2(\omega)] + \lambda_1^* q_1(\omega) + \lambda_2^* q_2(\omega)] dF(\omega),$$

where k^* denotes the multiplier associated with the target constraint and λ_i^* the multiplier associated with the non-negativity constraint for pollutant i for $i = 1, 2$. With $\{q_1^*(\omega), q_2^*(\omega)\}_{\omega \in \Omega}$ denoting the solution to the program, we obtain the following first-order conditions:

$$\begin{aligned} B_1(q_1^*(\omega), \bar{Q}_2) &= C_1(q_1^*(\omega), q_2^*(\omega), \omega) - \lambda_1^*, \\ k^* &= C_2(q_1^*(\omega), q_2^*(\omega), \omega) - \lambda_2^*, \end{aligned}$$

for every $\omega \in \Omega$. For the local pollutant, the marginal benefit of abatement should be equal to the marginal cost (net of the shadow value of the non-negativity constraints) in each country ω . For the global pollutant, marginal abatement costs (net of the shadow value of the non-negativity constraints) should be equal among countries and equal to the shadow value of the target. This is to say, the target \bar{Q}_2 should be decomposed into individual abatement efforts $q_2^*(\omega)$ per country to satisfy the equimarginal principle.

Assume an interior solution for abatement of the two pollutants so that the non-negativity constraints are not binding and $\lambda_1^* = \lambda_2^* = 0$ (the assumption of interior solution is discussed later). Substituting the functional forms for abatement benefits and costs, we obtain:

$$\begin{aligned} a_1 - b_1 q_1^*(\omega) &= m q_1^*(\omega) + \omega q_2^*(\omega), \\ k^* &= m q_2^*(\omega) + \omega q_1^*(\omega), \end{aligned}$$

for every $\omega \in \Omega$. This leads to:

$$q_1^*(\omega) = \frac{a_1 m - \omega k^*}{m b_1 + m^2 - \omega^2}, \quad (6)$$

$$q_2^*(\omega) = \frac{k^* [b_1 + m] - a_1 \omega}{m b_1 + m^2 - \omega^2}, \quad (7)$$

for every $\omega \in \Omega$. For $\omega = 0$, i.e., no interaction between the two pollutants, equations (6) and (7) simplify to $q_1^*(0) = \frac{a_1}{b_1 + m}$ and $q_2^*(0) = \frac{k^*}{m}$. Thus, the abatement effort in the local pollutant $q_1^*(\omega)$ does not depend on the global pollution target \bar{Q}_2 . For $\omega \neq 0$, it does. A higher global target \bar{Q}_2 means a higher common marginal cost k^* to reach this target, which impacts the marginal cost of abating the local pollutant. If the two pollutants are complements, i.e., $\omega < 0$, it becomes cheaper to abate pollutant 1 so $q_1^*(\omega)$ increases. Reversely, if pollutants are substitutes, meaning $\omega > 0$, abatement of global pollution makes abatement of local pollution more expensive. Thus, $q_1^*(\omega)$ decreases with a higher target \bar{Q}_2 .

As shown in appendix A, for a given global emissions target, abatement of both pollutants decreases with ω *regardless* of its sign. In particular, for two interaction parameters ω^- and ω^+ of the same magnitude $|\omega^+| = |\omega^-|$ but different sign $\omega^+ > 0 > \omega^-$, cost-efficient abatement is always higher for both pollutants when they are complements rather than substitutes: $q_1^*(\omega^-) > q_1^*(\omega^+)$ and $q_2^*(\omega^-) > q_2^*(\omega^+)$. This is because the equimarginal principle requires more abatement from countries with the lowest abatement cost and therefore with the lowest ω . Hence more abatement is required from countries where pollutants are complements than from countries where pollutants are substitutes.

Before examining environmental regulations, we discuss the assumption of an interior solution for abatement in the cost-efficient solution. Comparing (4) and (6) shows that the non-negative constraint is binding when $\omega > \frac{ma_1}{k^*}$. It might hold when the two pollutants are substitutes and the target global abatement level \bar{Q}_2 is high (so that k^* is high compared to ω). In this case, the global pollution abatement target is so high that abatement of local pollution becomes too costly and, therefore, $q_1^*(\omega) = 0$ for every $\omega > \frac{ma_1}{k^*}$. Symmetrically, comparing (5) and (7) indicates that $q_2^*(\omega) = 0$ whenever $\omega > \frac{k^*}{a_1}[b_1 + m]$: abatement of the global pollutant is too costly. Let us assume that $\bar{\omega} \leq \min \left\{ \frac{ma_1}{k^*}, \frac{k^*}{a_1}[b_1 + m] \right\}$ to guarantee an interior solution in which abatement of both pollutants is required in the cost-efficient solution. Similarly, for expositional convenience, we assume that the conditions for an interior solution in abatement are met throughout the rest of the paper.

3 Local regulation in the shadow of future global regulation

We analyze a country's or local regulator's pollutant 1 abatement effort under the expectation that the global pollutant 2 will be regulated later on. The choice of instrument and its stringency is exogenous and perfectly forecasted by local regulators.⁴ We consider two regulatory instruments aimed to implement the same global target on emission abatement \bar{Q}_2 : emission caps at the country level (Section 3.1) and a tax on emissions (Section 3.2). Note that emission caps $\bar{e}(\omega)$ can be expressed in terms of abatement and therefore referred to as abatement quotas, i.e., $\bar{e}_2(\omega) = e_2^e(\omega) - \bar{q}_2(\omega)$, where $e_2^e(\omega)$ denotes uncontrolled emissions of the global pollutant and $\bar{q}_2(\omega)$ represents the abatement quota for every $\omega \in \Omega$. In what follows, we consider successively the cost-efficient abatement quotas and a uniform abatement quota. We also examine tradable emission allowances and discuss the assignment of the revenue from taxing emissions. Next, we endogenize the emission abatement target in Section 3.3.

⁴A related study is Burtraw et al. (2012), who analyze the choice of policy instruments faced by an environmental regulator of a specific pollutant who anticipates subsequent regulation by a different regulator of another pollutant resulting from the same production process. Unlike our study, they assume that there is uncertainty regarding the choice of instrument and the stringency of the global regulation.

3.1 Abatement quotas

The global regulator commits to assign country-specific abatement quotas based on a cost-efficient allocation of the global abatement target. Given the timing of regulation, cost-efficiency is achieved ex post: after each country has set its own regulation on the local pollutant. This is to say, the global abatement target \bar{Q}_2 is split into local efforts $\bar{q}_2(\omega)$ in a way to equalize marginal cost of abatement of the global pollutant 2 given the choice of abatement for local pollutant $q_1(\omega)$. Formally, $\bar{q}_2(\omega)$ is such that:

$$C_2(q_1(\omega), \bar{q}_2(\omega), \omega) = \bar{k}, \quad (8)$$

for every $\omega \in \Omega$, where \bar{k} is a shadow cost of meeting the global abatement target \bar{Q}_2 with

$$\bar{Q}_2 = \int_{\underline{\omega}}^{\bar{\omega}} \bar{q}_2(\omega) dF(\omega).$$

The equimarginal principle (8) links abatement of both pollutants in a country to the marginal cost of meeting the target.⁵

Expecting that $\bar{q}_2(\omega)$ will be set such that condition (8) holds, a country of type $\omega \in \Omega$ chooses the abatement effort for local pollution $q_1(\omega)$ that maximizes its own welfare defined by:

$$\max_{q_1(\omega)} B(q_1(\omega), \bar{Q}_2) - C(q_1(\omega), \bar{q}_2(\omega), \omega), \quad (9)$$

subject to the future global regulation in equation (8). Denoted $\bar{q}_1(\omega)$, the regulation of local pollution satisfies the following first-order condition:⁶

$$B_1(\bar{q}_1(\omega), \bar{Q}_2) = C_1(\bar{q}_1(\omega), \bar{q}_2(\omega), \omega) + C_2(\bar{q}_1(\omega), \bar{q}_2(\omega), \omega) \frac{d\bar{q}_2(\omega)}{d\bar{q}_1(\omega)}. \quad (10)$$

The marginal benefit of abating pollutant 1 should be equal to its marginal cost, which is decomposed into two terms: a *direct* cost (the first term on the right-hand side) and an *indirect* cost (the second term on the right-hand side). The indirect cost quantifies the impact of the local regulation on the marginal abatement cost of meeting the future quota on global abatement. It depends on how local regulation affects the future abatement quota and the marginal cost of meeting the quota. The impact of local regulation on the future global abatement quota can be found by differentiating the equimarginal principle in equation (8):

$$\frac{d\bar{q}_2(\omega)}{d\bar{q}_1(\omega)} = -\frac{C_{12}(\bar{q}_1(\omega), \bar{q}_2(\omega), \omega)}{C_{22}(\bar{q}_1(\omega), \bar{q}_2(\omega), \omega)}. \quad (11)$$

Since marginal abatement costs are convex, $C_{22} < 0$ and the denominator is always negative. Therefore, how $\bar{q}_2(\omega)$ varies with $q_1(\omega)$ depends on the sign of the cross derivative C_{12} . If $C_{12} < 0$, then

⁵Note that k^* and \bar{k} differ for the same target Q_2 when $q_2^*(\omega) \neq \bar{q}_2(\omega)$ because, as we show later, the marginal costs of abating pollutant 2 are not the same.

⁶Recall that we assume an interior solution. The non-negativity constraint on abatement can therefore be ignored.

the variation is positive: a more stringent local regulation leads to more abatement of global pollution. The cross derivative being negative corresponds to *complement* pollutants. In this case, the two regulations are *strategic complements*: a more stringent regulation of local pollution leads to a more stringent regulation on global pollution. The indirect effect of marginal cost is then positive as more abatement of local pollution increases the marginal cost of abating global pollution.

Reversely, $C_{12} > 0$ in case of *substitute* pollutants. The variation is then negative: a more stringent local regulation leads to less abatement of global pollution. The two regulations are *strategic substitutes*. The indirect effect on marginal cost is then negative because abatement of local regulation reduces the marginal cost of abating global pollution.

To sum-up, the indirect effect of local regulation on pollution abatement through future global abatement depends on whether the two pollutants are complements or substitutes in abatement cost. This determines whether regulations are strategic complements or strategic substitutes. The indirect effect increases the costs of abating the local pollutant if pollutants are complements and decreases the costs if they are substitutes.

Using our functional form, equation (11) simplifies to:

$$\frac{d\bar{q}_2(\omega)}{d\bar{q}_1(\omega)} = \frac{-\omega}{m}. \quad (12)$$

One more unit of local pollution abatement modifies the country's abatement of global pollution by $\frac{-\omega}{m}$. It leads to an increase of abatement $\bar{q}_2(\omega)$ if $\omega < 0$. Reversely, less abatement $\bar{q}_2(\omega)$ is required for the country ω when $\omega > 0$.

Substituting (10) and solving for $\bar{q}_1(\omega)$ with the functional forms, we obtain:

$$\bar{q}_1(\omega) = \frac{ma_1}{mb_1 + m^2 - \omega^2}, \quad (13)$$

for every $\omega \in \Omega$. Using (13), we obtain abatement levels for global pollution:

$$\bar{q}_2(\omega) = \frac{\bar{k}}{m} - \frac{a_1\omega}{mb_1 + m^2 - \omega^2}. \quad (14)$$

Note that the abatement quota is always binding even with economies of scope in abatement efforts. Indeed, when $\omega < 0$, $\bar{q}_2(\omega)$ can be expressed as a function of the unregulated abatement effort on global pollutant $q_2^e(\omega)$ as:

$$\bar{q}_2(\omega) = \frac{\bar{k}}{m} + q_2^e(\omega).$$

Hence, $\bar{q}_2(\omega) > q_2^e(\omega)$ for every $\omega \in \Omega$ as long as the global abatement cap is binding so that $\bar{k} > 0$.

Comparing (13) with (6), we obtain the departure from the cost-efficient solution with the same target \bar{Q}_2 for every country type $\omega \in \Omega$:

$$\bar{q}_1(\omega) - q_1^*(\omega) = \frac{\omega k^*}{mb_1 + m^2 - \omega^2}.$$

With no interaction between the two pollutants $\omega = 0$, a country cannot influence the choice of future quota on global pollution through its actual choice of local regulation. Hence, the two abatement efforts coincide, i.e., $q_1^*(0) = \bar{q}_1(0) = \frac{a_1}{b_1 + m}$. With interaction between the two pollutants $\omega \neq 0$, the departure depends on both the sign and the magnitude of the interaction parameter ω . Local pollution is under-abated $\bar{q}_1(\omega) < q_1^*(\omega)$ when pollutants are complements $\omega < 0$ and over-abated $\bar{q}_1(\omega) > q_1^*(\omega)$ when they are substitutes $\omega > 0$. When pollutants are complements, the country reduces the regulation stringency for local pollution to avoid being assigned a more stringent global abatement quota. Reversely, with substitute pollutants, the country would be assigned a less stringent quota if it increases abatement of local pollution. Moreover, the strategic effect of domestic regulation on the future quota on abatement of global pollution increases with the magnitude of the interaction parameter ω since the departure from the cost-efficient solution increases with the absolute value of ω .⁷ Furthermore, the departure from the cost-efficient solution is higher for a more stringent global target \bar{Q}_2 as the difference between $\bar{q}_1(\omega)$ and $q_1^*(\omega)$ increases with the shadow value of the cost-efficient solution k^* .

Note that the same outcome would be achieved if the local pollutant were regulated with a tax on emissions $\tau_1(\omega)$ rather than a quota $\bar{q}_1(\omega)$ for each country $\omega \in \Omega$. Since the tax is levied by the country itself, it does not show up in its objective function; it is paid by firms but redistributed to local firms or consumers. In this case, the tax rate that maximizes country ω 's welfare satisfies the following first-order condition:

$$B_1(q_1^\tau(\omega), \bar{Q}_2) \frac{dq_1^\tau(\omega)}{d\tau_1} = C_1(q_1^\tau(\omega), \bar{q}_2(\omega), \omega) \frac{dq_1^\tau(\omega)}{d\tau_1} + C_2(q_1^\tau(\omega), \bar{q}_2(\omega), \omega) \frac{d\bar{q}_2(\omega)}{dq_1^\tau(\omega)} \frac{dq_1^\tau(\omega)}{d\tau_1},$$

which, after simplifying, boils down to the condition (10).

We thus are able to enunciate a first result.

Proposition 1 *Under differentiated abatement quotas for global pollution, countries over-abate local pollution compared with the cost-efficient abatement if pollutants are substitutes and under-abate local pollution if pollutants are complements.*

Hence, the way abatement of global pollution is shared among countries does impact the stringency of local pollution regulation when the two pollutants interact in abatement cost. Here it is done in a cost-efficient way ex post, i.e., once the regulation on local pollution has been designed. Since the stringency of the local regulation impacts the marginal cost of abating the global pollutant, countries influence their assigned abatement quota $\bar{q}_2(\omega)$ by modifying the abatement cost. By increasing the marginal cost of abating the global pollutant, a country is required to abate less. Marginal cost is

⁷Formally, differentiating $\bar{q}_1(\omega) - q_1^*(\omega)$ with respect to ω leads to $\frac{k^* [mb_1 + m^2 + \omega^2]}{[mb_1 + m^2 - \omega^2]^2} > 0$. Therefore, $\bar{q}_1(\omega) - q_1^*(\omega)$ is increasing in ω when ω is positive and $q_1^*(\omega) - \bar{q}_1(\omega)$ is decreasing with ω when ω is negative.

increased (decreased) with more abatement of the local pollutant when pollutants are substitutes (complements). Therefore, a country over-abates local pollution when pollutants are substitutes and under-abates when they are complements.

As mentioned in the introduction, this result is related to the literature on countries' strategies under the expectation of a future climate agreement, which studies how pre-negotiation policy decisions are made with an eye on the future negotiations. For instance, Beccherle and Tirole (2011) make the point that unilaterally abating GHG emissions puts a country in a bad position for future negotiations. Similarly, Harstad (2015) shows that future climate change deals deter innovation since countries hold upon their R&D investment efforts. In our paper, the stringency of the local regulation causes similar effects: if the global and local pollutants are complements (substitutes) in abatement, the countries put themselves in a bad position for future negotiations by increasing (decreasing) the abatement of the local pollutant. Hence, with regards to the cost-effective abatement efforts, they under-abate (over-abate) the local pollutant in order to strengthen their positions.

For global pollution, the departure from cost-efficient abatement with quotas in a given country ω can be computed as the difference between (7) and (14):

$$\bar{q}_2(\omega) - q_2^*(\omega) = \frac{[\bar{k} - k^*] [mb_1 + m^2] - \bar{k}\omega^2}{m [mb_1 + m^2 - \omega^2]}. \quad (15)$$

It is decomposed into two terms in the numerator. The first term is the same for all countries regardless of ω and depends on $\bar{k} - k^*$, which is the difference between the marginal costs under differentiated quotas and the cost-efficient solution. It is strictly positive because marginal costs are by definition minimized under the cost-efficient solution (and the two solutions differ as long as $\omega > 0$ for some $\omega \in \Omega$). The second term is negative and depends on the magnitude of ω but not on its sign. Since both abatements quota $\bar{q}_2(\omega)$ and $q_2^*(\omega)$ sum up to the same target, it should dominate the first term for large ω countries. This means that countries whose ω is large in absolute terms will under-abate compared with the first best. In contrast, countries whose ω is close to zero will be asked to over-abate global pollution, because then $\bar{q}_2(\omega) - q_2^*(\omega) \approx \frac{\bar{k} - k^*}{m} > 0$.

Using (15), we can compute the threshold absolute value of ω for which the two abatement levels coincide:

$$\tilde{\omega} = \sqrt{\frac{[\bar{k} - k^*] [mb_1 + m^2]}{\bar{k}}}.$$

We thus have shown the following proposition.

Proposition 2 *Under differentiated abatement quotas on global pollution, there exists a threshold $\tilde{\omega}$ on the cost interaction parameter ω that defines whether countries under-abate or over-abate global pollution compared with the cost-efficient solution: they over-abate if $|\omega| < \tilde{\omega}$ and under-abate if $|\omega| > \tilde{\omega}$.*

When global pollution is expected to be regulated under differentiated quotas that minimize abatement costs, countries strategically regulate their local pollution to impact their future quota. This strategic effect reduces efficiency and thus increases the abatement cost of reaching a given global emission target. Those who suffer the most from this increased cost are countries with a low interaction parameter because they are asked to abate more than with the cost-efficient solution. Countries with a high interaction parameter benefit from the strategic effect: they manage to get less stringent abatement quotas than the cost-efficient solution.

Before moving on to emission tax, we want to stress that this strategic effect of environmental regulation arises because abatement quotas are assigned cost-efficiently. The effect would disappear if the assignment rule were unrelated to abatement costs, for instance with abatement quotas defined per capita or GDP. If in our model, emission reductions per capita were to be the same, each country would abate the same, defined as $\bar{q}_2(\omega) = \bar{Q}_2$ for every $\omega \in \Omega$.⁸ In such a case, countries would take the abatement of global pollution as given and the local regulation would be set at an efficient level, i.e., by equalizing the marginal benefit of abatement to its marginal cost. However, the cost of achieving the target \bar{Q}_2 would not be minimized as abatement costs are not equalized. Yet the relative performance of these two second-best policies is not obvious.

As shown in Appendix B, countries for which pollutants are substitutes would prefer differentiated quotas as in such case they obtain more abatement of local pollution and less abatement of global pollution. In contrast, countries for which pollutants are complements are better off with uniform quotas.

3.2 Tax on global pollution and tradable emissions permits

Let us assume that the global regulator commits to achieve the same global abatement \bar{Q}_2 with a (uniform) tax τ_2 on emissions of the global pollutant 2 instead of abatement quotas. Abatement levels $q_2^\tau(\omega)$ will be such that firms equalize the marginal abatement cost for the global pollutant to the tax rate in every country $\omega \in \Omega$:

$$C_2(q_1(\omega), q_2^\tau(\omega), \omega) = \tau_2. \quad (16)$$

Importantly, assume further that a country's emissions do not impact its share of revenue collected from taxing emissions, e.g., the revenue is shared equally among countries or redistributed according to a rule that does not depend on emissions. Let us first assume that countries set quantity targets for abatement of local pollution, e.g. emission caps. Country ω chooses the abatement effort $q_1(\omega)$ that maximizes its benefit net of abatement cost and tax payments:

$$B(q_1(\omega), \bar{Q}_2) - C(q_1(\omega), q_2^\tau(\omega), \omega) - \tau_2 [e_2^e(\omega) - q_2^\tau(\omega)], \quad (17)$$

⁸Recall that, with a continuum of countries of mass one, total abatement Q_2 is also the average abatement level.

where $q_2^\tau(\omega)$ satisfies (16) for every $\omega \in \Omega$. The first-order condition yields:

$$B_1(q_1(\omega), \bar{Q}_2) = C_1(q_1(\omega), q_2^\tau(\omega), \omega) + [C_2(q_1(\omega), q_2^\tau(\omega), \omega) - \tau_2] \frac{dq_2^\tau(\omega)}{dq_1(\omega)}. \quad (18)$$

Country ω chooses the abatement effort such that the marginal benefit of abating pollution equals its marginal cost. The marginal cost is composed of the direct (first right-hand side term) and indirect (second right-hand side term) effects of a future choice of global pollution abatement $q_2^\tau(\omega)$. Now, however, one more unit of global pollution abatement $q_2^\tau(\omega)$ has two impacts: it increases the marginal abatement cost and reduces tax payments. The two impacts cancel out since the global abatement target will be chosen such that the marginal abatement cost of each country $C_2(q_1(\omega), q_2^\tau(\omega), \omega)$ equals the tax rate τ_2 . Thus, the first-order condition (18) leads to the cost-efficient condition in every country $\omega \in \Omega$:

$$B_1(q_1(\omega), \bar{Q}_2) = C_1(q_1(\omega), q_2^\tau(\omega), \omega). \quad (19)$$

Hence, for a given global cap \bar{Q}_2 , the cost-efficient outcome is implemented with a tax on global pollution of $\tau_2 = k^*$ per unit of emission. Such a tax rate would lead each country $\omega \in \Omega$ to implement an abatement quota $q_1^*(\omega)$. The firm in country ω binds the quota by abating $q_1^*(\omega)$. Moreover, each country will choose abatement $q_2(\omega)$ such that the marginal cost of abatement equalizes the tax rate τ_2 . We thus obtain the cost-efficient abatement levels of both of the local and global pollutants.

The cost-efficient outcome can also be achieved if the local pollutant is regulated with a tax on emissions τ_1 rather than a quota on abatement. The tax rate implemented by a country of type ω maximizes the same objective as in (17). The choice of abatement of local pollution satisfies the following first-order condition:

$$B_1(q_1(\omega), \bar{Q}_2) \frac{dq_1(\omega)}{d\tau_1} = C_1(q_1(\omega), q_2^\tau(\omega), \omega) \frac{dq_1(\omega)}{d\tau_1} + [C_2(q_1(\omega), q_2^\tau(\omega), \omega) - \tau_2] \frac{dq_2(\omega)}{d\tau_1},$$

which, after decomposing $\frac{dq_2^\tau(\omega)}{d\tau_1} = \frac{dq_2^\tau(\omega)}{dq_1(\omega)} \times \frac{dq_1(\omega)}{d\tau_1}$ and simplifying, boils down to the efficiency condition (19).

It is worth mentioning that the revenue from taxing emissions of global pollution should not be assigned to the country hosting the polluting firm. Otherwise, the payment of the tax disappears from the local regulator's objective in (17) (last term). The tax would then be missing in the first-order condition (18) which determines regulation stringency of the local pollutant. The first-order condition (18) would then become similar to condition (10) and, therefore, we end up with the same distortion in regulation stringency as with cost-efficient differentiated abatement quotas. We thus conclude that to obtain efficiency, each country should pay for the externality its activities generate on global pollution through emission taxes.

Finally, the cost-efficient outcome can also be achieved by using tradable emission permits rather than taxing the global pollutant. The intuition is similar as for the tax instrument. Assume that each

country or firm is assigned $l_2(\omega)$ units of tradable emission allowances. Denote by $q_2^t(\omega)$ the level of abatement effort of the firm in country ω for every $\omega \in \Omega$. The initial allocation of permits must achieve the target reduction of global pollution:

$$\bar{Q}_2 = \int_{\underline{\omega}}^{\bar{\omega}} [e_2^e(\omega) - l_2(\omega)] dF(\omega) = \int_{\underline{\omega}}^{\bar{\omega}} q_2^t(\omega) dF(\omega), \quad (20)$$

where the last equality is due to the permit market-clearing condition. The firm in country ω chooses abatement levels denoted $q_2^t(\omega) = e_2^e(\omega) - l_2(\omega)$ to equalize the marginal abatement cost for the global pollutant to the equilibrium price of permits in every country $\omega \in \Omega$:

$$C_2(q_1(\omega), q_2^t(\omega), \omega) = p_2. \quad (21)$$

Country ω 's objective when choosing abatement effort $q_1(\omega)$ now includes the net position of firms in the permit market:

$$B(q_1(\omega), \bar{Q}_2) - C(q_1(\omega), q_2^t(\omega), \omega) - p_2 [e_2^e(\omega) - l_2(\omega) - q_2^t(\omega)], \quad (22)$$

where $q_2^t(\omega)$ and p_2 satisfy (21) for every $\omega \in \Omega$ as well as the market-clearing condition (20). Since each firm or country has a negligible impact on the price of emission allowances p_2 , the first-order condition yields:

$$B_1(q_1(\omega), \bar{Q}_2) = C_1(q_1(\omega), q_2^t(\omega), \omega) + [C_2(q_1(\omega), q_2^t(\omega), \omega) - p_2] \frac{dq_2^t(\omega)}{dq_1(\omega)} - p_2 \frac{dl_2(\omega)}{dq_1(\omega)} \quad (23)$$

for every ω . This first-order condition is similar to (16) with the price of emission permits p_2 instead of the tax τ_2 . The last term $\frac{dl_2(\omega)}{dq_1(\omega)}$ captures the impact of abating local pollution on the initial allocation of emission permits. It is nil when the initial allocation of permits is unrelated to local pollution. In such case, the first-order condition boils down to the efficiency condition (19) since the permit price is equal to marginal cost. Since the total number of permits is defined by the emission target \bar{Q}_2 , the equilibrium permit price is $p_2 = k^*$. We thus obtain efficiency: $q_i^t(\omega) = q_i^*(\omega)$ for every $\omega \in \Omega$ and every pollutant $i = 1, 2$.

Yet permits might be initially allocated according to a rule that depends on local pollution abatement. For instance, the allocation might be proportional to abatement costs in the sense that a country with higher abatement costs obtains more permits. Then countries will tend to distort the stringency of their local regulations to obtain more permits. Formally, the last term remains in the first-order condition, which means that abatement is not efficient. Since $\frac{dl_2(\omega)}{dq_1(\omega)} = \frac{\omega}{m}$, it holds that countries over-abate local pollution compared with the cost-efficient abatement if pollutants are substitutes and under-abate local pollution if pollutants are complements to obtain more permits.⁹

We summarize our results in the following proposition.

⁹The fact that firms have incentives for strategic action if allocation in one period depends on previous actions is well known in the literature. See, e.g., Sterner and Muller (2008), who show that free allocation of permits is bound to create problems.

Proposition 3 *Regulations on local and global pollution are efficient if the target on global pollution is implemented by emission taxes or tradable emission permits provided that (i) the revenue from taxing emissions are redistributed to the countries independently of emissions, and (ii) the initial allocation of permits is not linked to abatement costs.*

Unlike non-tradable differentiated abatement caps, setting a tax on global pollution does not lead to an inefficient outcome. Even if the country takes into account the effect of its local regulation on the cost of abating the global pollutant, this cost is compensated by the tax saved. The tax rate reflects the social marginal cost of abatement, which is the same ex post. Therefore each country internalizes the impact of its regulation choice on the social cost of abating the global pollutant. To internalize this impact, the tax should be returned to countries in a non-distortionary way. Similarly, efficiency is achieved with emission permits at country level as long as the initial allocation of permits is not influenced by local regulation. Otherwise, a country has an interest in distorting its local regulation to obtain more permits, as with non-tradable differentiated abatement caps.

Before endogenizing the global pollution target, let us discuss the robustness of our results to alternative regulatory timing. We show in Appendix C that efficiency is achieved with cost-efficient abatement costs if both regulators (local and global) move simultaneously or if the global regulator moves first. This is true regardless of the policy instrument used, i.e., abatement quota, tax, or tradable permits. Indeed, the strategic effect of local environmental policy on quota abatement or emission allowances disappears when the two pollutants are regulated simultaneously. When the global pollutant is regulated first, the global regulator implements a first best abatement level because it aims to maximize social welfare at the world level. We would obtain suboptimal regulation of global pollution with a global regulator who ignores or disregards the damages of local pollution, for example, because it is not in the mandate of the federal or international regulatory agency or values the welfare of a subset of countries (for example, because not all countries join the international environmental agreement). When it comes to taxes, Proposition 3 holds when the two regulations are designed simultaneously or in the reverse order, i.e., global regulator moving first.

3.3 Efficient future abatement target

In this section, we endogenize the choice of global emission target. Let us assume now that the abatement target for the global pollutant \bar{Q}_2 is set taking into account the benefit of abating global pollution. Let \bar{Q}_2^* and Q_2^* denote the efficient global abatement under differentiated quotas and under tax (or, equivalently, tradable permits), respectively. It is common knowledge among countries and firms that abatement of the global pollutant will be set to maximize social welfare given regulations on local pollution $q_1(\omega)$. The global regulator chooses abatement of the global pollutant at the country

level $q_2(\omega)$ for every $\omega \in \Omega$ to maximize social welfare defined by:

$$\int_{\underline{\omega}}^{\bar{\omega}} [B(q_1(\omega), Q_2) - C(q_1(\omega), q_2(\omega), \omega)] dF(\omega), \quad (24)$$

subject to $Q_2 = \int_{\underline{\omega}}^{\bar{\omega}} q_2(\omega) dF(\omega)$. The first-order condition leads to the equalization of marginal benefit to marginal cost for every $\omega \in \Omega$:

$$B_2(q_1(\omega), Q_2) = C_2(q_1(\omega), q_2(\omega), \omega), \quad (25)$$

which, with our functional forms, yields:

$$a_2 - b_2 Q_2 = m q_2(\omega) + \omega q_1(\omega). \quad (26)$$

The efficiency conditions (26) are defined by different abatement levels $q_1(\omega)$ depending on the instrument used to regulate the global pollutant. With differentiated abatement quotas, the analysis in Section 3.1 applies: countries set local regulations to induce abatement efforts $\bar{q}_1(\omega)$ defined in (13) for every $\omega \in \Omega$. With a tax on global pollution, we already know from Section 3.2 that the local abatement efforts would be cost-efficient $q_1^*(\omega)$. Abatement of local pollution is then given by equation (6) where $k^* = a_2 - b_2 Q_2^*$ since, by definition, the global target Q_2^* is set at the efficient level. Combining equation (6) with $k^* = a_2 - b_2 Q_2^*$ and (13) yields:

$$\omega [\bar{q}_1(\omega) - q_1^*(\omega)] = \frac{\omega^2 [a_2 - b_2 Q_2^*]}{m b_1 + m^2 - \omega^2}, \quad (27)$$

which is strictly positive regardless of ω . Integrating condition (26) for all $\omega \in [\underline{\omega}, \bar{\omega}]$ leads to

$$Q_2 = \frac{[a_2 - E(\omega q_1(\omega))]}{b_2 + m}. \quad (28)$$

The global abatement target with tax Q_2^* is defined by equation (28) with $q_1(\omega) = q_1^*(\omega)$, where $q_1^*(\omega)$ is defined in (6). The one under quota \bar{Q}_2^* is also defined by equation (28), but with $q_1(\omega) = \bar{q}_1(\omega)$, where $\bar{q}_1(\omega)$ is defined in (13). Using equation (27), we obtain $\bar{Q}_2^* < Q_2^*$: aggregate abatement of the global pollutant is lower under differentiated abatement quotas than under tax. The reason is that differentiated quotas distort the stringency of local regulations, which increases the cost of abating the global pollutant in all countries. The equalization of abatement cost to the marginal benefit of abatement leads to less abatement and thus more emissions in total than the first best (or with taxes). From the analysis, it also follows that since the abatement levels differ under the two instruments and the tax implements the first best, total welfare must be lower under quotas. Thus, the implementation of non-tradable differentiated abatement quotas will not only distort the stringency of local pollution abatement but also lead to under-abatement of the global pollutant.

Proposition 4 *The global abatement target is lower under differentiated abatement quotas than under tax.*

A final remark concerns the effects of the choice of policies to implement an international climate agreement and the incentives to deviate from it. It is well known that the lack of an effective international government vested with effective coercive powers makes it unlikely that adequate participation in and compliance with an international climate treaty will be achieved. Free-riding behavior can be expressed through non-participation or non-compliance. As shown in Appendix D, for the countries for which pollutants are substitutes and the absolute value of ω is large, it holds that the welfare gains of non-compliance are larger when the agreement is implemented through taxes than through differentiated quotas. Thus, for those countries, the less cost-effective regulation is more likely to be effective in promoting participation in and compliance with international climate agreements. Interestingly, Barrett and Stavins (2003) reach a similar conclusion. They find that proposals that are best in terms of cost-effectiveness (conditional on implementation) – primarily market-based instruments such as tradable permit regimes – are less likely to be effective in promoting participation in and compliance with international climate agreements. In our setting, differentiated non-tradable abatement quotas provide countries for which pollutants are substitutes (and hence, which in relative terms have the highest cost of compliance with a climate treaty) with implicit transfers through reduced abatement responsibilities. Thus, despite the fact that taxes can reduce costs overall, differentiated non-tradable abatement quotas are most likely to induce compliance by countries with high costs.

4 Big country

Let us analyze how robust our results are to the assumption of atomistic countries. Indeed, it is well known that the climate change problem is characterized by the existence of a few large emitters such as China and the United States. To account for this in our model, we consider a dominant country denoted by the superscript D . This country is responsible for a share μ of global abatement. We first examine the case of abatement quotas that are set cost-efficiently ex post with an endogenous emission target on global pollution. The dominant country of type ω^D chooses an abatement level q_1^D that maximizes its welfare subject to the abatement quotas on global pollution for itself \bar{q}_2^D and a level of global abatement for global pollution \bar{Q}_2 defined by $\bar{Q}_2 = \mu\bar{q}_2^D + [1 - \mu]\bar{Q}_2^{-D}$, where \bar{Q}_2^{-D} denotes total abatement by other countries:

$$\bar{Q}_2^{-D} = \int_{\underline{\omega}}^{\bar{\omega}} \bar{q}_2(\omega) dF(\omega).$$

In such case, the first-order condition in (10), determining the optimal level of abatement of local pollution, becomes:

$$B_1(\bar{q}_1^D, \bar{Q}_2) = C_1(\bar{q}_1^D, \bar{q}_2^D, \omega^D) + [\mu B_2(\bar{q}_1^D, \bar{Q}_2) - C_2(\bar{q}_1^D, \bar{q}_2^D, \omega^D)] \frac{d\bar{q}_2^D}{d\bar{q}_1^D}. \quad (29)$$

Hence, if $\mu = 1$ there will be full internalization of the global warming externality. In contrast, if $\mu = 0$, we are back to our original case. Whenever $0 < \mu < 1$, part of the global warming externality is not internalized and, therefore, the outcome is inefficient.

For tradable emission permits, the question naturally arises as how our results would change in the presence of a dominant country that can manipulate the market to its own advantage by means of its choice of abatement of the local pollutant.¹⁰ To analyze this problem, let l_2^D denote the number of emission permits freely distributed to the dominant country. Assume further that l_2^D is determined independently of abatement costs. The dominant country chooses the abatement effort q_1^D that maximizes the benefit from local abatement net of abatement cost and payments for net permit transactions. This yields the following first-order condition:

$$B_1(q_1^D, \bar{Q}_2) = C_1(q_1^D, q_2^D, \omega^D) + [p_2 - C_2(q_1^D, q_2^D, \omega^D)] \frac{dq_2^D}{dq_1^D} - \frac{dp_2}{dq_1^D} [e_2^{\varepsilon D} - l_2^D - q_2^D].$$

This equation differs from the case of atomistic countries in (10) by $\frac{dp_2}{dq_1^D}$ which captures the impact of the dominant country's environmental policy on the price of permits. The price equalizes marginal abatement costs in all countries as in (21). By summing up all those conditions for all countries, we are able to express explicitly the price as a function of abatement levels from both the dominant and the atomistic countries:

$$p_2 = \mu [mq_2^D + \omega^D q_1^D] + [1 - \mu] \int_{\underline{\omega}}^{\bar{\omega}} mq_2(\omega) + \omega q_1(\omega) dF(\omega).$$

Differentiating the above equation with respect to $q_1^D(\omega)$, we obtain

$$\frac{dp_2}{dq_1^D} = \mu \omega^D.$$

Hence, if $\mu = 0$ we are back to the efficiency condition (19). Yet if $\mu > 0$, the outcome is inefficient. How it departs from efficiency depends on the interaction parameter of the dominant country and whether the dominant country is a net buyer or a net seller in the market for permits (i.e., whether the net demand for permits $e_2^{\varepsilon D} - q_2^D$ exceeds the initial allocation l_2^D). With economies of scope $\omega^D < 0$, abating local pollution reduces the price of emission permits because it decreases the cost of abating the global pollutant. As a consequence, a net buyer dominant country over-abates local pollution (while the reverse holds if the dominant country is a net seller of permits). Symmetrically, with dis-economies of scope $\omega^D > 0$, abating local pollution increases the price of emission permits through higher abatement costs for global pollution. If the dominant country is a net buyer (seller) of permits, it under-abates (over-abates) local pollution compared with the efficient level. Thus, when the dominant country is a net seller of permits, we obtain results similar to those under cost-efficient non-tradable abatement quotas described in Section 3.1. In contrast, our results indicate that a

¹⁰See Hahn (1984) for a formal analysis of such manipulation.

dominant country that is a net buyer of permits will over-abate (under-abate) local pollution when pollutants are complements (substitutes) in order to reduce the price of emission permits.

5 Conclusion

Having analyzed the interplay between local and global pollution with spillovers in abatement costs, we are able to answer the question raised in the introduction: Are the spillovers between local air pollution and GHG emissions good news for the climate? Our analysis shows that the answer depends on several ingredients: (i) whether efforts to reduce local air pollution and GHG emissions are substitutes or complements in cost, (ii) whether GHG emissions are regulated or not at the international level, (iii) the choice of instrument used to implement an international agreement on GHG reduction, and (iv) the marginal impact of countries on total GHG emissions.

First, without any international obligation for GHG emissions, it is in each country's own interest to reduce its GHG emissions when local air pollution and GHG abatement efforts are complements. Doing so, the country exploits economics of scope in pollution abatement. This is so even if each country has a negligible impact on global GHG emissions. In contrast, when abatement efforts are substitutes, countries have no self-interest in reducing GHG emissions. In fact, the regulation of local air pollution might lead to higher GHG emissions.

Second, when GHG are regulated internationally, the choice of instrument and timing of regulation matter. In particular, if countries expect GHG emissions to be regulated in the future through cost-efficient non-tradable emissions caps, they have an incentive to distort the stringency of their own domestic regulation of local air pollution to obtain higher emission caps. Whether the regulation is too stringent or not stringent enough depends on the sign of the spillover effect in abatement cost. In any case, even if the emission caps are set cost-efficient ex post (once domestic regulations of local air pollution have been implemented), they are distorted: the same target for global GHG emissions is achieved at a higher cost. If this target is chosen to maximize social welfare, it is set too lax compared with the first best. In this case, the policy spillover effect is bad for the climate. A similar distortion in local air pollution arises with a tax on GHG emissions when each country keeps all the revenue from taxing emissions within its territory. To avoid this distortion, the revenue from taxing GHG emissions should be assigned to a country independently of its own contribution. Similarly, emission caps or allowances should not depend on abatement costs, e.g., per capita or GDP.

Third, the strategic distortion of local regulation is mitigated for "big" countries that have a significant impact on global GHG emissions. Big GHG emitters would partly internalize how their choice of local air pollution affects GHG emissions, which undermines this strategic effect. This holds for cost-efficient emission caps but not for tradable permits: a big country might distort its local air

pollution regulation to manipulate the price of permits. How it departs from the first best depends on the dominant country's abatement cost spillover and whether the country is a net buyer or a net seller in the market for permits. For instance, we find that a dominant country that is a net buyer of permits will over-abate (under-abate) local pollution when pollutants are complements (substitutes) in order to reduce the price of emission permits. In contrast, the incentives are reversed when the dominant country is a net seller of permits.

From our analysis, we can conclude that a country's concerned by local air pollution is good news for the in the absence of any international obligation on GHG emissions when there are economies of scope (or ancillary benefits) in abatement costs. Furthermore, the cost interaction between abatement local and global pollution matters for the choice of regulation instruments for GHG emissions for the reasons explained above.

The model in this paper is simplified in a number of respects to keep the analysis tractable. For example, we do not model a potential interaction between the two pollutants in the damage they cause. Such an extension could be easily incorporated it in our model in line with the analysis of Ambec and Coria (2013). In such case, the distortions would depend on the net effect of the interactions between the two pollutants in damages and costs. In addition, our analysis assume perfect information. Moreover, the economies (diseconomies) of scale are assumed to be exogenous. However, firms have private information about their abatement costs. That is, firms know whether they are more productive reducing one of the pollutants and, if so, to what degree. Furthermore, economies (dis-economies) are endogenous to the choice of abatement technologies installed in response to environmental regulations. Finally, moral hazard, adverse selection, and endogenous technological progress are problems that complicate the analysis of the conflicts created by non-cooperative regulations and are as such left as areas for further research.

A Comparison of first-best abatements given \bar{Q}_2

Differentiating equation (6) with respect to ω yields:

$$q_1^{*\prime}(\omega) = \frac{2\omega [a_1 m - \omega k^*] - k^* [mb_1 + m^2 - \omega^2]}{[mb_1 + m^2 - \omega^2]^2}. \quad (30)$$

Note that $a_1 m - \omega k^* \geq 0$ because $q_1^*(\omega) \geq 0$ for every $\omega \in \Omega$. Further, $m^2 - \omega^2 > 0$ by assumption. Therefore, we can conclude that $q_1^{*\prime}(\omega) < 0$ for every $\omega \leq 0$ so that $q_1^*(\omega)$ is decreasing when pollutants are complements.

Similarly, differentiating equation (7) with respect to ω yields:

$$q_2^{*\prime}(\omega) = \frac{2\omega [k^* [b_1 + m] - a_1 \omega] - a_1 [mb_1 + m^2 - \omega^2]}{[mb_1 + m^2 - \omega^2]^2}. \quad (31)$$

Note that $k^* [b_1 + m] - a_1 \omega \geq 0$ for every $q_2^*(\omega) \geq 0$. Further, $m^2 - \omega^2 > 0$ by assumption. Therefore, we can conclude that $q_2^{*\prime}(\omega) < 0$ for every $\omega \leq 0$ so that $q_2^*(\omega)$ is decreasing when pollutants are complements.

Furthermore, for any ω^- and ω^+ such that $|\omega^+| = |\omega^-|$ and $\omega^+ > 0 > \omega^-$, we have $q_1^*(\omega^-) > q_1^*(\omega^+)$ and $q_2^*(\omega^-) > q_2^*(\omega^+)$. Therefore, by continuity $q_1^*(\omega)$ and $q_2^*(\omega)$ are decreasing with ω when $\omega > 0$, i.e., when pollutants are substitutes.

B Country's welfare comparison between cost-efficient differentiated and uniform quota

Let us compare the welfare difference between uniform and differentiated quotas. For simplicity, let us assume that ω can take two values: ω^- and ω^+ , where $\omega^- < 0 < \omega^+$. For a fraction κ of the countries $\omega = \omega^-$, and hence for the remaining fraction $[1 - \kappa]$ it holds that $\omega = \omega^+$. Under a uniform quota, the abatement of the global pollutant corresponds to $q_2^U = \kappa q_2^*(\omega^-) + [1 - \kappa] q_2^*(\omega^+)$. Hence $q_2^*(\omega^+) < q_2^U < q_2^*(\omega^-)$.

Let us compare q_2^U with the abatement of the global pollutant under differentiated cost-efficient quotas $\bar{q}_2(\omega)$.

If $\omega = \omega^-$, we have:

$$\bar{q}_2(\omega^-) - q_2^U = [\bar{q}_2(\omega^-) - q_2^*(\omega^-)] + [1 - \kappa] [q_2^*(\omega^-) - q_2^*(\omega^+)].$$

The sign of the difference $[\bar{q}_2(\omega^-) - q_2^*(\omega^-)]$ is not straightforward. However, by Proposition 2 we know that it is positive when $|\omega^-| < \tilde{\omega}$, and hence, $\bar{q}_2(\omega^-) - q_2^U > 0$. Furthermore, we know that $\frac{\partial \bar{q}_2(\omega)}{\partial \omega} < 0$. Hence, $\bar{q}_2(|\omega^-| > \tilde{\omega}) > \bar{q}_2(|\omega^-| < \tilde{\omega})$ and therefore $\bar{q}_2(\omega^-) - q_2^U > 0 \vee \omega^-$.

If $\omega = \omega^+$, we have:

$$\bar{q}_2(\omega^+) - q_2^U = [\bar{q}_2(\omega^+) - q_2^*(\omega^+)] - \kappa [q_2^*(\omega^-) - q_2^*(\omega^+)].$$

By Proposition 2 we know that $\bar{q}_2(\omega^+) - q_2^U < 0$ if $|\omega^+| > \tilde{\omega}$. Furthermore, we know that $\frac{\partial \bar{q}_2(\omega)}{\partial \omega} < 0$. Hence, $\bar{q}_2(|\omega^+| < \tilde{\omega}) > \bar{q}_2(|\omega^+| > \tilde{\omega})$ and therefore $\bar{q}_2(\omega^+) - q_2^U > 0 \vee \omega^+$.

When it comes to local pollution we know that:

$$\begin{aligned} \bar{q}_1(\omega) - q_1^U(\omega) &= [\bar{q}_1(\omega) - q_1^*(\omega)] + [q_1^*(\omega) - q_1^U(\omega)] \\ &= \omega \left[\frac{k^*}{mb_1 + m^2 - \omega^2} + \frac{[q_2^U(\omega) - q_2^*(\omega)]}{m + b_1} \right]. \end{aligned}$$

This expression is unambiguously positive $\vee \omega^+$, and hence $\bar{q}_1(\omega^+) > q_1^U(\omega^+)$. However, the comparison is less clear for ω^- . After some further calculations, and assuming that $\omega^- = -\omega^+$, this expression can be represented as:

$$\bar{q}_1(\omega^-) - q_1^U(\omega^-) = \omega^- \left[\frac{k^* [m + b_1] + 2 [1 - \kappa] a_1 \omega^-}{mb_1 + m^2 - [\omega^-]^2} \right].$$

We know that $k^* [m + b_1] + a_1 \omega^- > 0$ for $q_2^*(\omega^-) > 0$. Therefore, we can say that $\bar{q}_1(\omega^-) < q_1^U(\omega^-)$ when $\kappa \leq \frac{1}{2}$.

This is to say, with regards to differentiated quotas, uniform quotas imply less abatement of local pollution and more abatement of global pollution for the countries for which pollutants are substitutes. The reverse holds for countries for which pollutants are complements. Finally, the difference in welfare between uniform and differentiated quotas can be represented as $\Delta W_1(\omega)$, given by:

$$\begin{aligned} \Delta W_1(\omega) &= [q_1^U(\omega) - \bar{q}_1(\omega)] \left[a_1 - \frac{[b_1 + m]}{2} [q_1^U(\omega) + \bar{q}_1(\omega)] \right] \\ &+ [Q_2^* - \bar{Q}_2^*] \left[a_2 - \frac{b_2}{2} [Q_2^* + \bar{Q}_2^*] \right] + \frac{m}{2} [\bar{q}_2(\omega)^2 - [q_2^U]^2] + \omega [\bar{q}_1(\omega) \bar{q}_2(\omega) - q_1^U(\omega) q_2^U]. \end{aligned} \quad (32)$$

As shown in Section 3.3., $\bar{Q}_2^* < Q_2^*$. Moreover, when $\omega = 0$ this expression simplifies to:

$$\Delta W(\omega) = [Q_2^* - \bar{Q}_2^*] \left[a_2 - \frac{b_2}{2} [Q_2^* + \bar{Q}_2^*] \right] + \frac{m}{2} [\bar{q}_2(\omega)^2 - [q_2^U]^2] > 0.$$

Finally, let us have a look at the last term. We can show that for $\omega^+ = -\omega^-$, this expression corresponds to:

$$\omega^+ [\bar{q}_1(\omega^+) \bar{q}_2(\omega^+) - q_1^U(\omega^+) q_2^U] = \omega^+ \left[\frac{a_1 m [\bar{q}_2(\omega^+) - q_2^U]}{mb_1 + m^2 - \omega^2} - \frac{[q_2^U \omega^+]}{[m + b_1]} \left[\frac{k^* [m + b_1] + 2 [1 - \kappa] a \omega^-}{mb_1 + m^2 - \omega^2} \right] \right].$$

Therefore, $\omega^+ [\bar{q}_1(\omega^+) \bar{q}_2(\omega^+) - q_1^U(\omega^+) q_2^U] < 0$ if $\kappa \leq \frac{1}{2}$. Thus, countries for which pollutants are substitutes are in relative terms worse off under uniform quotas since the first, third and fourth term in parentheses on the RHS of equation (32) are negative.

C Regulatory Timing

We show that optimality is achieved either when both regulators move simultaneously or the global regulator moves first regardless of the choice of policy instruments. Let us consider first the case of simultaneous regulation. In line with Section 3.1., the maximization problem of the global regulator yields FOCs:

$$C_2(\bar{q}_1(\omega), \bar{q}_2(\omega)) = \hat{k},$$

for every $\omega \in \Omega$, where \hat{k} is the shadow cost of reaching the target \bar{Q}_2 that could be equal to the first best level, in which case \hat{k} is the marginal benefit of abating the global pollutant.

Country ω chooses an abatement quota $\bar{q}_1(\omega)$ to maximize the net welfare defined in (9). Since the abatement quotas are decided simultaneously, $\frac{d\bar{q}_2(\omega)}{d\bar{q}_1(\omega)} = 0$ and hence equation (10) simplifies to:

$$B_1(\bar{q}_1, \bar{Q}_2) = C_1(\bar{q}_1(\omega), \bar{q}_2(\omega)). \quad (33)$$

Therefore, the first best is achieved since countries choose an abatement quota $\bar{q}_1(\omega)$ such that the marginal benefit of abating pollution equals the marginal costs and the global regulator chooses abatement quotas $\bar{q}_2(\omega)$ such that countries equalize their marginal cost to the marginal benefit of abating the global pollutant 2.

Let us consider now the case of sequential regulation where pollutant 2 is regulated before pollutant 1 through differentiated quotas $\bar{q}_2(\omega)$. Since country ω takes the stringency of the quota $\bar{q}_2(\omega)$ as given, the quota $\bar{q}_1(\omega)$ that maximizes welfare is such that the marginal benefit of abating pollution equals the marginal costs. In contrast, the quota $\bar{q}_2(\omega)$ that maximizes the global regulator's optimization problem satisfy the following FOC:

$$\left[\hat{k} - C_2(q_1(\omega), q_2(\omega)) \right] + \left[B_1(q_1, \bar{Q}_2) - C_1(q_1(\omega), \bar{q}_2(\omega)) \right] \frac{d\bar{q}_1(\omega)}{d\bar{q}_2(\omega)} = 0. \quad (34)$$

However, since $B_1(\bar{q}_1, \bar{Q}_2) = C_1(\bar{q}_1(\omega), \bar{q}_2(\omega))$ we end up with the efficient FOC. The same argument shows that the first best is achieved with a tax on local pollution 1 rather than abatement quotas.

Simultaneous implementation of taxes will also lead to first best. The firm in country of type ω reacts to the tax rate τ_i for pollutant i by equalizing its marginal abatement cost to the tax rate for $i = 1, 2$:

$$\tau_i = C_i(q_i, q_j, \omega). \quad (35)$$

The global regulator chooses the tax rate τ_2 to maximize social welfare at the world level (24) subject to the reaction functions defined by (35). This yields the following FOC:

$$\left[B_2(q_1^\tau, Q_2) - C_2(q_1^\tau, q_2^\tau, \omega) \right] \frac{dq_2^\tau}{d\tau_2} + \left[B_1(q_1^\tau) - C_1(q_1^\tau, q_2^\tau, \omega) \right] \frac{dq_1^\tau}{d\tau_2} = 0, \quad (36)$$

As discussed in Section 3.2., the tax rate τ_1 that maximizes country ω 's welfare satisfies the following FOC:

$$[B_1(q_1^\tau) - C_1(q_1^\tau, q_2^\tau, \omega)] \frac{dq_1^\tau}{d\tau_1} - [C_2(q_1^\tau, q_2^\tau, \omega) - \tau_2] \frac{dq_2^\tau}{d\tau_1} = 0. \quad (37)$$

Given (35), the FOC in (37) simplifies to $B_1(q_1^\tau) = C_1(q_1^\tau, q_2^\tau, \omega)$. Hence, the FOC in (36) becomes $B_2(q_1^\tau, Q_2) = C_2(q_1^\tau, q_2^\tau, \omega)$, implying that the first best is achieved when regulators decide on the tax levels $\tau_1(\omega)$ and τ_2 simultaneously.

Finally, let us consider the case when both pollutants are regulated by taxes and the global regulator moves first. Like in the simultaneous case, country ω chooses a tax level $\tau_1(\omega)$ such that the marginal benefit of abating pollution equals the marginal costs. In contrast, the tax level τ_2 that maximizes the global regulator's optimization problem satisfies the following FOC:

$$[B_2(Q_2^\tau) - C_2(q_1^\tau, q_2^\tau, \omega)] \frac{dq_2^\tau}{d\tau_2} + [B_1(q_1^\tau) - C_1(q_1^\tau, q_2^\tau, \omega)] \frac{dq_1^\tau}{d\tau_2} = 0. \quad (38)$$

However, since $B_1(q_1^\tau) = C_1(q_1^\tau, q_2^\tau, \omega)$, this condition simplifies and thus the tax τ_2 is set at a level such that countries equalize their marginal cost to the the marginal benefit of abating pollutant 2.

D Welfare variation from participating in an international agreement on global pollution

We assume that a country ω that deviates from the international agreement chooses the abatement levels $q_1^e(\omega)$ and $q_2^e(\omega)$, which maximize welfare in the absence of international regulation of global pollution. In contrast, the global aggregate abatement corresponds to the first best Q_2^* and can be implemented through differentiated abatement quotas or a carbon tax. Let $W^L(\omega)$ denote country ω 's welfare when deviating from the agreement. Moreover, let $\bar{W}(\omega)$ and $W^*(\omega)$ denote country ω 's welfare when the agreement is implemented through differentiated cost-efficient abatement quotas and taxes, respectively.

The welfare gains of deviating from an agreement that implements Q_2^* through taxes are larger than the welfare gains of deviating when the agreement is implemented through quotas if:

$$W^L(\omega) - W^*(\omega) > W^L(\omega) - \bar{W}(\omega). \quad (39)$$

Condition (39) simplifies to:

$$\Delta W_2(\omega) = \bar{W}(\omega) - W^*(\omega) > 0.$$

Given the functions of abatement benefits and costs, ΔW_2 can be represented as:

$$\begin{aligned} \Delta W_2(\omega) &= [\bar{q}_1(\omega) - q_1^*(\omega)] \left[a_1 - \frac{[b_1 + m]}{2} [\bar{q}_1(\omega) + q_1^*(\omega)] \right] + \frac{m}{2} \left[[q_2^*(\omega)]^2 - [\bar{q}_2]^2 \right] \\ &\quad + \omega [q_1^*(\omega) q_2^*(\omega) - \bar{q}_1(\omega) \bar{q}_2] + \tau_2 [e_2^0(\omega) - q_2^*(\omega)], \end{aligned} \quad (40)$$

which simplifies to:

$$\Delta W_2(\omega) = [\omega \bar{k}]^2 - m[b_1 + m] \left[[\bar{k}]^2 - [k^*]^2 \right] + 2mk^* [mb_1 + m^2 - \omega^2] [e_2^e(\omega) - q_2^*(\omega)]. \quad (41)$$

Note that $\Delta W_2(\omega)$ is decomposed into three terms. The first term is positive and depends on the magnitude of ω but not on its sign. The second term is negative since the difference $[\bar{k} - k^*]$ is strictly positive. Finally, the third term is positive since the difference $[e_2^e(\omega) - q_2^*(\omega)]$ is strictly positive for every $\omega \in \Omega$. Furthermore, as shown in Appendix A, $q_2^*(\omega)$ is decreasing with ω for every $\omega \in \Omega$, implying less abatement of global pollution by the countries for which pollutants are substitutes. In addition, the uncontrolled emissions of global pollutant $e_2^e(\omega)$ are expected to be larger for those countries since they do not abate at all in the absence of a global regulation. Thus, we can conclude that $\Delta W_2(\omega)$ is decreasing with ω for every $\omega \in \Omega$ and that it is larger for countries for which pollutants are substitutes.

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