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Does leadership in policy setting reduce pollution and make countries better off?

Ornella Tarola * & Emmanuelle Taugourdeau †

Abstract

In light of the ongoing debate on Common But Differentiated Responsibilities (CBDR), we wonder whether it is worthwile for industrialized countries to take the lead in reducing emissions, rather than acting simultaneously with less advanced countries. To do this, we compare national payoffs and global emissions in each situation. We also examine whether industrial leakage is an inevitable outcome of asymmetric policies with differentiated abatement responsibilities and, if so, whether unambigously hurts the more industrialized countries. We show that leadership can improve payoffs while reducing global emissions, even though these goals appear to be at odds.

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1 Introduction

It is well established that while firms operating within a country contribute to its economic growth, they also generate pollution. Consequently, regulators face the challenge of balancing two key priorities: national economic prosperity and environmental protection. However, environmental protection and, more specifically, pollution mitigation measures impose a dramatically costly effort and, thus, feeds the argument that abating emissions cannot come but at expenses of wealth. For that reason, the rationale for sharing the environmental duties between more and less industrialized countries is strongly debated. On the one hand, less industrialized countries claim that they have only recently acquired the capacity to sustain economic development. Thus, the industrialized countries should lead the way in decarbonizing the world, and less industrialized countries should follow. Efforts should also be differentiated: the less industrialized countries should have less obligations than their more advanced counterparts. On the other hand, industrialized countries argue that taking the lead in emissions reduction and accepting a *regime of differentiated contributions* (known as *Common But Differentiated Responsibilities,* or *CBDRs*) could have serious negative consequences. The primary concern is the risk of *industrial leakage*, where firms might relocate from countries with stricter policies to those with more lenient ones. Moreover, while environmental legislation is generally a national concern, pollution remains a global issue. The pollution level in one area is often affected by emissions originating elsewhere, known as *transboundary emissions*[1]. This makes environmental policies even more controversial, as transboundary considerations contribute to determine their stringency at local level. Why industrialized countries should accept to pay for pollution mitigation when emissions are partially generated by less industrialized countries?

Our contribution to this debate examines whether global emissions are reduced and countries benefit more when industrialized nations take the lead in reducing emissions, rather than acting simultaneously with less advanced countries. The benefit for each country is assessed by taking into account both its national wealth and the environmental damage it incurs. We also explore whether industrial leakage is an inevitable outcome of asymmetric policies with differentiated abatement responsibilities and, if so, it unambigously hurts the more industrialized countries.

By means of a very stylized model, we show that, *(i)* contrary to the common wisdom, when the more industrialized country assumes the lead role in abatement, both the more industrialized and the less industrialized countries can be better off. Even more interestingly, *(ii)* under certain conditions, taking the lead can align two seemingly opposing objectives: safeguarding national

[1] There is for example ample evidence of cross-border pollution in Asia: Japan and South Korea regularly complain that the acid rain they suffer is caused by emissions of sulfur and nitrogen oxides from coal-burning plants in northern China (Abu Sayed, "Cross-border pollution : A growing international problem", The Daily Star, February 19, 2011.)

economic prosperity while effectively reducing global emissions. This may happen even in presence of an industrial leakage phenomenon. In this circumstance, we say that the sequential game equilibrium dominates the simultaneous equilibrium. At first glance, the rationale behind this is straightforward: including transboundary emissions in the damage function amplifies the negative impact a country experiences when global emissions are high. Consequently, each country is incentivized to adopt stringent environmental policies, which positively affects both its national payoff and global environmental objectives. However, the argument is no longer as simple if we consider at the same time the effects that this policy generates on firms initially located in that country, i.e. industrial leakage, and the possibility opened to the country to manipulate taxes to affect firms' flow. Finally *(iii)*, we show that differentiated policies do not necessarily drive firms to relocate to countries with less stringent environmental regulations; market asymmetries and additional policy tools can attract firms to industrialized countries, even when these countries adopt more stringent environmental policies. Said differently, industrial leakage is not an inevitable consequence of asymmetric environmental policies.

To explore this, we consider a game where two players—a more industrialized country and a less industrialized country—set their national environmental policies. These countries are asymmetric, differing in production costs and their initial firm endowments. Additionally, they have varying levels of tolerance for pollution, with the more advanced country being less tolerant. This difference arises because, historically, emission reduction targets have been more ambitious for industrialized countries than for less industrialized ones. *Environmental policies* are not treated as independent; we assume that in addition to implementing climate mitigation measures, governments also aim to enhance their economic wealth through *corporate taxes*.[2] Taxes are designed to attract firms, while environmental policies, although effective in reducing emissions, may drive firms to relocate.

Formally, the game develops as follows: countries initially establish their policies, and then firms decide whether to relocate based on the policies each country implements. They determine whether relocation is more advantageous than remaining in their current locations. When setting their policies, we assume that countries may play simultaneously or sequentally, with the more advanced country being the leader. Countries take into account both domestic and transboundary emissions when defining their *local policies.* Additionally, to formalize the *countries'payoffs*, we introduce a combination of *economic wealth* and *environmental damage.* All else being equal, economic wealth increases with the number of firms within a country, while environmental damage

[2]The literature in public economics on the effects of tax competition on firms' location choices has a long-standing tradition. Empirical evidence shows that countries are involved in strategic competition to attract capital *via* corporate taxes thereby avoiding firms' relocation.

improves as pollution levels decrease. We describe the equilibrium configuration of the game in terms of *countries' payoffs* and *global emissions*, comparing how the equilibrium outcomes differ when countries act simultaneously versus sequentially. Additionally, we briefly examine how the game's equilibrium changes when countries adopt environmental policies from a purely local perspective—ignoring transboundary emissions and treating emissions in one geographic area as having no impact elsewhere.

Our contribution is linked to different streams of literature. Although the structure of international agreements for climate change has been extensively investigated (Barrett, 1994; Carraro and Siniscalco, 1998; Finus, 2003; Rubio and Ulph, 2006), to the best of our knowledge, scarce attention has been paid by the theoretical literature to the effects that sequential or simultaneous environmental policies may generate. Bárcena-Ruiz (2006) studies whether governments prefer to be leaders or followers when deciding their environmental taxes. It is found that whether governments prefer to be leaders or followers in taxes depends on the degree to which environmental pollution spills over to trading partners. More recently, MacKenzie (2011) considers governments' sequential allocation choices in a tradable permit market, whereas in a similar vein, Lapan and Sikdar (2011) analyse the effect of sequential setting of pollution taxes with a specific focus on the carbon leakage phenomenon. Bednar-Friedl (2012) considers the potential effects of acting first when emission reduction benefits and costs are based on technological differences in aggregate production functions (emission intensity, production elasticity of capital and labor), saving rates, and heterogeneous household preferences with respect to global warming. We are close in spirit to these papers. We borrow the idea that pollution is transboundary and countries are asymmetric. However, considering in a unified framework environmental policies and corporate taxes puts our paper far from the above contributions.

Our analysis is also related to another strand of extensive and multifaceted literature on the trade-off between national wealth and world emissions. It delves into the complex relationship between competitiveness, industrialization, and environmental sustainability. Many studies have explored the adverse impacts on domestic firms of stringent climate policies, thereby showing that industrial leakage can be induced when unilateral policies are put in place (Maria and Van der Werf, 2008; Ikefuji et al., 2016; Sanna-Randaccio et al., 2017; Fischer et al., 2017). Although our primary concern is not analysing whether industrial leakage is always observed in presence of asymmetric environmental policies, we contribute to this literature as firms' flow from a country to another plays a key role in our model and contributes to determine the equilibrium properties.

Finally, a literature on a necessary sustainable degrowth movement has been initiated. This literature advocates for alternative economic models, such as a steady-state economy and doughnut economics, which prioritize ecological stability and social well-being over perpetual growth (Martínez-Alier et al., 2010; Kallis, 2011). Our model does not aim to study the relevance of the degrowth movement, but it questions the trade-off between national payoff and global emissions, which remains at the heart of this literature.

The paper proceeds as follows. In the next section, we describe the main features of the model. Section 3 presents the equilibria depending of the timing of the game. Section 4 deals with the effect of the timing of the game on countries' payoff and world emissions by comparing the different equilibria and section 5 concludes.

2 The model

We consider an economy composed of two countries, 1 and 2. We denote by n_i $\forall i = 1, 2$ the number of firms in country i, with $n_1 + n_2$ fixed. Then, $s_i \equiv \frac{n_i}{n_i+n_j}$, $\forall j = 1, 2$ and $i \neq j$, is the index of firms' endowment in country i, with $s_1 + s_2 = 1$. We consider that country 1 is initially endowed with at least as many firms as country 2 so that $s_1 \geq \frac{1}{2}$. This implies that country 1 is considered as an *industrialized* country, whereas country 2 is a *less industrialized* country.[3]

Country i is environmentally conscious and is impacted by emissions resulting from production. This impact is reflected in their national payoff function through a damage function D_i. As pollution is a global phenomenon, the damage relies on domestic emissions E_i and transboundary emissions E_j; the latter being generated by emissions spillover flowing from country j to country i. To curb emissions, country $i = 1, 2$ sets an environmental policy defined by an emissions tolerance index α_i. Also, countries have tax autonomy and levy a lump sum corporate tax t_i on their tax base.[4] The difference in the initial endowment of firms implies that country 1 benefits from a larger initial tax base. Setting a tax on the tax base generates a revenue R_i, which is the second component of the government's payoff function in each country.

We consider a game where governments set their optimal policy, i.e. their environmental policy α_i, besides their corporate taxes t_i, $i = 1, 2$, while firms decide where to locate, after observing the policy mix (t_i, α_i) in each country.[5] Countries are aware that pollution is a global issue.

[3] The term "advanced economy", as used by the International Monetary Fund (IMF), refers to the world's most developed countries. While there is no strict numerical criteria for classifying an economy as advanced, these nations are typically characterized by high per capita income and a substantial degree of industrialization. Although our assumption on s_1 aligns with the IMF's classification, examples like China and Russia, which are considered by the IMF as emerging economies, present notable exceptions.

[4] As in (Haufler and Wooton, 1999; Pieretti and Zanaj, 2011) we consider a lump sum tax on profit which corresponds to a tax per unit of capital

[5] As we will clarify in the following section, the environmental policy takes the form of an index of pollution

When defining their policy tools, governments face a trade-off. On one hand, they aim to reduce pollution and boost tax revenue by implementing stringent environmental policies and raising taxes. These direct effects tend to push firms away, acting as a *centrifugal force*. On the other hand, governments want to attract firms to expand their tax base, which encourages them to adopt more lenient environmental policies and lower corporate taxes – a *centripetal force*. However, a stringent environmental policy might decrease the number of firms that choose to remain in the country. Thus, the government might opt to set higher corporate taxes to compensate for the smaller tax base. The policy instruments selected and, consequently, the number of firms in each country at equilibrium are determined by the balance between these opposing centripetal and centrifugal forces.

2.1 Firms

Each firm is run by a worker-entrepreneur and is endowed with one unit of capital. The fixed quantity q produced by each firm is sold on a competitive world market at a price which is taken as given by the firm. Without loss of generality, we normalize the price to one.
When producing the output q, a firm in country $i = 1, 2$ incurs a cost C_i given by:

$$C_i(q, \bar{\alpha}_i - \alpha_i) = \chi_i(q) + q \times \nu(\bar{\alpha}_i - \alpha_i)$$

The cost function has two components: a variable manufacturing cost, $\chi_i(q)$ and an abatement cost $\nu(\bar{\alpha}_i - \alpha_i)$ per unit of production.

The manufacturing cost $\chi_i(q)$ is assumed to be country-specific and for simplicity we consider a linear cost in q, i.e. $\chi_i(q) = c_i q$. We assume that the industrialized country bears a higher manufacturing cost so that $c_1 > c_2$ and we denote $\Delta c = c_1 - c_2 > 0$.[6]

As far as the abatement cost per unit of production $\nu(\bar{\alpha}_i - \alpha_i)$ is concerned, it is decreasing in the *index of environmental tolerance* α_i set by country i, i.e. $\frac{\partial \nu(\bar{\alpha}_i - \alpha_i)}{\partial \alpha_i} < 0$: the higher the tolerance index, the lower the abatement effort required from firms in that country, *ceteris paribus*. The parameter $\bar{\alpha}_i$, instead, represents the index of emissions tolerance at the *status quo. i.e.* in the absence of any new environmental policy. If the government in country i maintains the current tolerance index (i.e $\alpha_i = \bar{\alpha}_i$), the abatement cost for firms is zero, meaning they are not required to make any effort to reduce emissions. Thus, their technologies and management practices are

tolerance. Thus, it defines the total amount of emissions per unit of output that a country tolerates in its area.

[6]Our assumption relies on the empirical evidence. The manufacturing cost is related to labour costs and raw materials, inter alia. Although wages in China have advanced enormously in the last 10 years in contrast to what has occurred in EU, labor cost is still lower in China than in EU. Moreover, the European Commission is talking about "strategic autonomy". Nonetheless, China is still a fundamental component of the supply chain.

considered to be sufficiently clean by the government in country i.[7] Instead, when the environmental policy decreases the index of tolerance so that $\alpha_i < \bar{\alpha}_i$, firms in country i must undertake a costly effort to curb emissions. Based on stylized facts, we assume that the industrialized country has a lower index of tolerance at the *status quo* than the less industrialized country: $\bar{\alpha}_2 > \bar{\alpha}_1$.[8]

From now on, we assume a quadratic abatment cost: $\nu(\bar{\alpha}_i - \alpha_i) = \frac{1}{2}(\bar{\alpha}_i - \alpha_i)^2$.

2.2 Governments

Governments are assumed to maximize their tax revenues net of environmental damage. Formally, the payoff functions of country i is given by[9]:

$$G_i(\alpha_i, t_i, \alpha_j, t_j) = R_i - D_i.$$

The first component R_i is the revenue obtained by the Government i when taxing at t_i firms located in country i, with

$$R_i = N_i t_i \tag{1}$$

where N_i measures the number of firms in country i after relocation of firms,

$$N_1 = \begin{cases} s_1(1-x) & if\ x > 0 \\ s_1 - xs_2 & if\ x < 0 \end{cases} \quad \text{and} \quad N_2 = \begin{cases} s_2 + xs_1 & if\ x > 0 \\ s_2(1+x) & if\ x < 0 \end{cases} \tag{2}$$

The revenue R_i, thus, represents the economic wealth of country i.

The second component D_i is the environmental damage suffered by country i, given by

$$D_i(E_i, E_j) = \gamma(E_i + \phi_j E_j)$$

where $\gamma \in]0, \bar{\alpha_1}[$ is the marginal damage.[10] The damage D_i depends on both emissions generated by firms in country i, namely *domestic emissions* $E_i = qN_i\alpha_i\ \forall i = 1, 2$ and emissions generated by firms in country j, namely *transboundary emissions* $E_j = qN_j\alpha_j$. To grasp the distinct effects of domestic and transboundary emissions on the damage in country i, we weight the transboundary

[7] In a different view, the index of emissions tolerance $\bar{\alpha}_i$ can be interpreted as firms' carbon emissions in country i in absence of any new investment in green technologies.

[8] In the past, the emission reduction target for the industrialized countries has been more ambitious than for the less industrialized countries. The difference in the index of tolerance at the status quo captures this trend.

[9] This government objective function takes the form of a partial Leviathan. We also assume absentee non-resident ownership of firms.

[10] A linear damage function is standard in the literature (see for example (Ceccantoni et al., 2018; Mantovani et al., 2016; Fowlie and Muller, 2019). This results in a constant marginal damage, which is commonly assumed in calibration exercises. A similar approach is also used by Marini et al. (2022). They introduce an environmental surplus that is linear in emissions and show how this surplus is linked to a linear environmental damage.

emissions by a parameter ϕ_j with $\phi_j \in]0,1]$. We assume that ϕ_j is country-specific and, *a priori*, $\phi_1 \gtreqless \phi_2$. This assumption reflects the evidence that the impact of pollution is influenced not only by the distance between countries but also by factors such as wind direction and speed, which vary between locations.[11]

3 The equilibrium analysis

We characterize the equilibrium configuration as follows. First, we assume that the countries' policies are set simultaneously, focusing on a simultaneous policy game, referred to as the SM game. Next, we examine the scenario where policies are set sequentially, known as the SK game. The last scenario embodies the notion of leadership that we examine in this article.
In each scenario, the final stage of the game corresponds to the firms' choice of location.

3.1 Location stage

Firms are imperfectly mobile and distributed over the interval $[0,1]$ in decreasing order of their willingness to relocate. The willingness to relocate of firm l, initially located in country i, is characterized by $x_{i,l}$. Following Pieretti and Zanaj (2011), we assume that relocating abroad costs firms a unit cost, $k < 1$.

Thereby, if firm l remains in country i, its profits are given by:

$$\pi^i_{i,l} = q - C_i(q, \bar{\alpha}_i - \alpha_i) - t_i \quad \forall i = 1,2$$

where t_i is the corporate tax set in country i.

Conversely, if firm l relocates from country i to country j, its profits are given by:

$$\pi^j_{i,l} = q - C_j(q, \bar{\alpha}_i - \alpha_j) - t_j - kx_{i,l} \quad \forall i = 1,2 \quad j = 1,2 \quad \text{and} \quad i \neq j.$$

By relocating in j, the firm previously located in country i must comply with the environmental policies of its new location. We assume that q is high enough to guarantee that, if firm l relocates from i to j, its profits are non-negative, i.e. $q \geq C_j(q, \alpha_j, \bar{\alpha}_i) + t_j + kx_{i,l}$.

[11] Moreover, they can change seasonally according to the activities taking place in a country. For example, in winter the temperature in northern China is lower than in southern China, and a greater amount of fossil fuels are burned for heating. As a consequence, the effect of pollution will be more significant in countries closer to northern China than in elsewhere.

From the indifferent condition between staying in country 1 or moving to country 2

$$q - \frac{1}{2}\left(\bar{\alpha}_1 - \alpha_1\right)^2 q - c_1(q) - t_1 = q - \frac{1}{2}\left(\bar{\alpha}_2 - \alpha_2\right)^2 q - c_2(q) - t_2 - kx_1 \tag{3}$$

we obtain that firms with $x_{1,l} < x_1$ prefer to relocate from 1 to 2 while firms with $x_{1,l} > x_1$ prefer to remain in country 1.

Symmetrically, considering a firm initially located in country 2 and indifferent between staying in country 2 or relocating to 1 leads to $x_2 = -x_1$. To simplify the notation, for the rest of the paper, we denote by $x = x_1 = -x_2$ the cut-off between staying in the industrialized country or relocating in the less industrialized one. From (3), we obtain

$$x(t_1, t_2, \alpha_1, \alpha_2) = \frac{1}{k}\Big((t_1 - t_2) + \frac{q}{2}\left((\bar{\alpha}_1 - \alpha_1)^2 - (\bar{\alpha}_2 - \alpha_2)^2\right) + \Delta c\Big) \tag{4}$$

The flow of firms from country i to country j, $i = 1, 2$ and $i \neq j$, depends on the tax gap, the emissions tolerance indices and the cost differential: when taxes and emissions gap are set so that $x > 0$, there is a positive flow of firms from 1 to 2. Conversely, when $x < 0$ firms flow from country 2 to country 1.

Note that the tax gap has a linear effect on the flow of firms (*linear tax incidence*) while the impact of emissions reductions on the flow is quadratic (*nonlinear emissions tolerance incidence*).

3.2 Policy decisions in the SM game

In the SM game, governments 1 and 2 simultaneously set their policy tools α_i (emissions tolerance index) and α_i and t_i, (tax rate), for $i = 1, 2$ in the first stage.[12]

Definition 1. *The equilibrium of the SM game is given by* $(t^*_{1,SM}, \alpha^*_{1,SM}, t^*_{2,SM}, \alpha^*_{2,SM})$.

To characterize the equilibrium, notice first that from the maximization of the payoff function $G_i(t_i, \alpha_i, t_j, \alpha_j)$ w.r.t the environmental policy α_i, the first order condition equates marginal damage to the marginal cost of abatment (See Appendix 6.1 for details):

$$\gamma = \bar{\alpha}_i - \alpha_{i,SM} \ \forall i = 1, 2$$

from which the optimal environmental policy can be immediately derived:

$$\alpha^*_{i,SM} = \bar{\alpha}_i - \gamma \ \forall i = 1, 2.$$

[12]We restrict our analysis to the case of positive taxes which implies $\Delta c_{t_2 SM} < \Delta c < \Delta c_{t_1 SM}$ (values of $\Delta c_{t_1 SM}$ and $\Delta c_{t_2 SM}$ are given in Appendix 6.2).

Since the *status quo* index of tolerance $\bar{\alpha}_i$ is lower in country 1 than in country 2, the environmental policy is always more stringent in the more industrialized country than in the less industrialized one ($\alpha^*_{1,SM} < \alpha^*_{2,SM}$). This stricter policy reflects the higher priority given to reducing emissions in the more advanced country.

Using $s_2 + s_1 = 1$, the equilibrium taxes are expressed as (See Appendix 6.1 for details):

$$t^*_{1,SM} = \frac{1}{3}\left[\frac{k(1+s_1)}{s_i} - q\Delta c + q\gamma\left((\bar{\alpha}_1 - \gamma)(1-\phi_1) + 2(\bar{\alpha}_2 - \gamma)(1-\phi_2) - (\bar{\alpha}_2 - \bar{\alpha}_1)\right)\right]$$

$$t^*_{2,SM} = \frac{1}{3}\left[\frac{k(1+s_2)}{s_i} + q\Delta c + q\gamma\left((\bar{\alpha}_2 - \gamma)(1-\phi_2) + 2(\bar{\alpha}_1 - \gamma)(1-\phi_1) + (\bar{\alpha}_2 - \bar{\alpha}_1)\right)\right]$$

where $s_i = s_1$ when $x^* > 0$, and $s_i = s_2$ when $x^* < 0$.

The equilibrium taxes are driven by three components. The *tax base driver*: this reflects the initial tax base, which tends to lead taxes in country 1 larger than taxes in country 2 *ceteris paribus*. As country 1 is assumed to start with a larger tax base and thus country 1 is less concerned about firm leakage than country 2 and can therefore set a higher level of tax. The *cost differential driver*: this factor drives down taxes in country 1 compared to country 2 since it gives a comparative advantage for country 2 in terms of attractiveness to firms, *ceteris paribus*. The *pollution driver*: this depends on both the pollution weights $(1 - \phi_i)$ and the *status quo* emission tolerance gap $(\bar{\alpha}_2 - \bar{\alpha}_1)$. This gap pushes down (resp. magnifies) $t^*_{1,SM}$ (resp. $t^*_{2,SM}$) as it makes country 2 more attractive for firms, putting pressure on country 1 to lower its taxes to remain competitive.

Given the equilibrium policies, the equilibrium flow of firms is:

$$x^*_{SM} = \frac{1}{3k}\left(\underbrace{\frac{k(s_1 - s_2)}{s_i}}_{\text{tax base driver}} + \underbrace{q\Delta c}_{\text{cost differential}} + \underbrace{q\gamma\left(\phi_1(\bar{\alpha}_1 - \gamma) - \phi_2(\bar{\alpha}_2 - \gamma) - (\bar{\alpha}_2 - \bar{\alpha}_1)\right)}_{\text{emissions weights effect}}\right) \qquad (5)$$

where $s_i = s_1$ when $x^* > 0$, and $s_i = s_2$ when $x^* < 0$.

The asymmetric initial tax base and the production cost differential Δc lead firms to leave country 1. Conversely, the *status quo* emission tolerance gap $(\bar{\alpha}_2 - \bar{\alpha}_1)$ induces firms to flow to country 1 which is counterintuitive since the status quo is more stringent is country 1 than in contry 2. This can be explained by the combination of the two policy tools. The equilibrium taxes internalise the repellent effect of the stricter environmental policy for firms and tries to compensate for this effect by decreasing t_2 and increasing t_1, which makes the effect of the *status quo* gap inverse to the excpeted direct effect. Finally and intuitively, more firms relocate when the mobility costs are lower.

The effect related to the transboundary emissions gap $(\phi_1(\bar{\alpha}_1 - \gamma) - \phi_2(\bar{\alpha}_2 - \gamma))$ is uncertain and depends on the ranking of the transboundary emissions weights ($\phi_1 \lesseqgtr \phi_2$). For $\phi_1 = \phi_2$, the gap is negative and, thus, the term induces firms to stay in country 1, thereby weakeaning the other drivers.[13]

Finally, it is worth noting that even in the absence of effective policy instruments ($t_i = 0$ and $\alpha_i = \overline{\alpha}_i$), the cost differential would be sufficient to induce a positive flow of firms from country 1 to 2. The lower production costs in country 2 make it an attractive option for firms, even without considering other factors such as taxes or environmental policies.

3.3 Policy decisions in the SK game

Let us now consider the SK game, which characterises the leadership of the industrialised country (see Kempf and Graziosi (2010); Kempf and Rota-Graziosi (2015)). Consequently, the government of country 1 first determines $\alpha_{1,SK}$ and $t_{1,SK}$, followed by country 2, which decides on $\alpha_{2,SK}$ and $t_{2,SK}$.

We explore whether, contrary to the typical first-mover advantage, the more advanced country is actually penalized when it adheres to the Common But Differentiated Responsibilities (CBDR) recommendation and takes the lead on pollution mitigation efforts.

Definition 2. *The equilibrium of the SK game is given by* $(t^*_{1,SK}, \alpha^*_{1,SK}, t^*_{2,SK}(t^*_1, \alpha^*_1), \alpha^*_{2,SK}(t^*_1, \alpha^*_1))$

We solve the game by backward induction. The maximization of country 2's payoff functions leads to the following best reply functions:

$$\alpha_{2,SK} = \bar{\alpha}_2 - \gamma \tag{6}$$

$$t_{2,SK}(t_{1,SK}, \alpha_{1,SK}) = \frac{1}{4}\left(\frac{2ks_2}{s_i} + 2q\Delta c + q\left((\bar{\alpha}_1 - \alpha_1)^2 - 2\alpha_1\gamma\phi_1 + 2\bar{\alpha}_2\gamma - 3\gamma^2\right) + 2t_1\right) \tag{7}$$

Note that the best reply functions highlight the role played by each policy instrument in country 2. More precisely, the index $\alpha_{2,S}$ is not affected by the policy instruments set by country 1. This is not true for $t_{2,SKS}$. The best reply function $t_{2,SK}(t_{1,SK}, \alpha_{1,SK})$ shows the linear tax incidence compared to the non linear tolerance incidence on firms mobility (see Expression (4)). Thus, in order to maximize its payoff, it is more efficient for the follower to adjust its tax in reaction to the strategy of the leader, instead of passing through the environmental policy.

[13]Moreover, $x^*_{SM} > 0 \iff \Delta c > \Delta c^+_{SM} \equiv \Gamma - \frac{k(s_1 - s_2)}{qs_1}$ while $x^*_{SM} < 0 \iff \Delta c < \Delta c^-_{SM} \equiv \Gamma - \frac{k(s_1 - s_2)}{qs_2}$ with $\Gamma = \gamma\left((\bar{\alpha}_2 - \bar{\alpha}_1) - \phi_2(\bar{\alpha}_2 - \gamma) + \phi_1(\bar{\alpha}_1 - \gamma)\right)$ which can be positive or negative.

The equilibrium configuration can be given as follows (detailed calculations are presenetd in Appendix 6.1):[14]

$$\begin{aligned}
\alpha^*_{1,SK} &= \bar{\alpha}_1 - \gamma(1+\phi_1) \text{ and} \\
t^*_{1,SK} &= \frac{1}{2}\left[\frac{k(1+s_1)}{s_i} - q\Delta c + q\gamma\left(\bar{\alpha}_2(1-\phi_2) + \bar{\alpha}_1(1-\phi_1) + \gamma\left(\phi_2 - \phi_1\right) - 2\gamma + \frac{1}{2}\gamma\phi_1^2\right)\right]
\end{aligned}$$

$$\begin{aligned}
\alpha^*_{2,SK} &= \bar{\alpha}_2 - \gamma \text{ and} \\
t^*_{2,SK} &= \frac{1}{4}\left[\frac{k(2+s_2)}{s_i} + q\Delta c + q\gamma\left(\bar{\alpha}_1(1-3\phi_1) + \bar{\alpha}_2(3-\phi_2) + \gamma(3\phi_1+\phi_2) - 4\gamma + \frac{7}{2}\gamma\phi_1^2\right)\right]
\end{aligned}$$

In contrast to the SM equilibrium, country 1 sets its environmental policy by internalizing the externalities caused by the pollution produced by its own firms on country 2. At first glance, the asymmetry in the design of environmental policies between the two countries—where transboundary emissions only influence the policy adopted by the advanced country—seems to confirm the argument of a first-mover disadvantage. In the following section, we will examine whether this argument holds true under closer scrutiny.

The equilibrium flow of firms x^*_S is given by:

$$x^*_{SK} = \frac{1}{4k}\left(\underbrace{\frac{k(2s_1 - s_2)}{s_i}}_{\text{tax base effect}} + \underbrace{q\Delta c}_{\text{cost differential}} + \underbrace{q\gamma\left(\phi_1(\bar{\alpha}_1 - \gamma) - \phi_2(\bar{\alpha}_2 - \gamma) - (\bar{\alpha}_2 - \bar{\alpha}_1) - \frac{\gamma}{2}\phi_1^2\right)}_{\text{emissions weights effect}}\right) \quad (8)$$

where $s_i = s_1$ when $x^* > 0$, and $s_i = s_2$ when $x^* < 0$.
Again, both the initial tax base effect and the cost differential positively affect the equilibrium flow of firms x^*.[15] As in the SM game, the only components that could induce firms to leave country 2 (so that $x^*_{SK} < 0$) are the transboundary parameters ϕ_1 and ϕ_2 and the difference in *status quo* tolerance index. Note that compared to the SM game, this component is reinforced by the term $\frac{\gamma}{2}\phi_1^2$ which reflects the leadership position of the more industrialized country, which either limits the outflow of firms from country 1 or increases the inflow of firms from country 2. Moreover, this effect can be offset by a larger tax base effect in the SK equilibrium than in the SM equilibrium.

[14] Again, we restrict our analysis to the case of positive taxes which implies $\Delta c_{t_2SK} < \Delta c < \Delta c_{t_1SK}$ (the values of Δc_{t_1SK} and Δc_{t_2SK} are given in Appendix 6.2).

[15] In particular, $x^*_{SK} > 0 \Longleftrightarrow \Delta c > \Delta c^+_S \equiv \Gamma + \frac{\gamma}{2}\phi_1^2 - \frac{k(2s_1-s_2)}{qs_1}$ and $x^*_{SK} < 0 \Longleftrightarrow \Delta c < \Delta c^-_S \equiv \Gamma + \frac{\gamma}{2}\phi_1^2 - \frac{k(2s_1-s_2)}{qs_2}$

3.4 SM versus SK policy instruments

We are now in the position to analyse how the equilibrium policies change with the timing of the game, in order to see whether a first mover disadvantage holds. The comparison between the environmental policies set at the SM or SK game is obvious, i.e :

$$\alpha^*_{1,SM} > \alpha^*_{1,SK} \quad \text{and} \quad \alpha^*_{2,SM} = \alpha^*_{2,SK},$$

Since $\alpha^*_{1,SM} > \alpha^*_{1,SK}$, *ceteris paribus*, country 1 is more attractive when policies are set simultaneously rather than sequentially.

As far as the differences in taxes is concerned, we find that:

$$\begin{aligned} t^*_{1,SM} &> t^*_{1,SK} \iff \Delta c > \Delta c_{t_1} \\ t^*_{2,SM} &> t^*_{2,SK} \iff \Delta c > \Delta c_{t_2} \end{aligned}$$

with

$$\begin{aligned} \Delta c_{t_1} &\equiv \Gamma + \frac{k(s_1+1)}{qs_1} + \frac{3}{2}\gamma\phi_1\left((\phi_1 - 4)\right) \text{ and} \\ \Delta c_{t_2} &\equiv \Gamma + \frac{k(s_1+1)}{qs_1} + \frac{21}{2}\gamma\phi_1^2 \end{aligned}$$

where $\Gamma = \gamma\left((\bar{\alpha}_2 - \bar{\alpha}_1) - \phi_1(\bar{\alpha}_1 - \gamma) + \phi_2(\bar{\alpha}_2 - \gamma)\right)$. We immediately deduce $\Delta c_{t_2} > \Delta c_{t_1}$.

Whathever the timing of the game, Δc pushes down the equilibrium tax in country 1 while pushing up the tax in country 2: country 1 restrains its tax to protect its tax base. The effect of the tax base goes in the opposite way. However, the tax in country 1 reacts much more strongly to the cost differential and the tax base in the SM scenario than in the SK scenario. As a result, for a very low cost asymmetry, the tax base effect is dominant and drives t_1 up and even more in the SK scenario. Then $t^*_{1,SM} > t^*_{1,SK}$. When the cost asymmetry increases, it pushes t_1 down but much faster in the SK scenario so that for a certain threshold, the tax at the SM equilibrium turns out to be lower than the tax set at the SK equilibrium.

For the ranking between $t^*_{2,SM}$ and $t^*_{2,SK}$ although both $t^*_{2,SM}$ and $t^*_{2,SK}$ are pushed up by the cost differential and the tax base, the effect of the cost differential is greater on $t^*_{2,SM}$ than on $t^*_{2,SK}$ while the opposite is true for the tax base effect due to the complementarity of taxes. Therefore, when the cost differential is small, the tax base effect dominates and $t^*_{2,SM} > t^*_{2,SK}$. As soon as the cost asymmetry increases, it pushes t_2 up, but much faster in the SK scenario, so that for a certain threshold, the tax at the SM equilibrium turns out to be lower than the tax set in the SK equilibrium.

4 The equilibrium dominance

In the following, we disentangle three issues. We wonder whether (i) when the more industrialized country assumes the lead role in abatement, both the more industrialized and the less industrialized country can be better off, *(ii)* under certain conditions, taking the lead can align two seemingly opposing goals: safeguarding national economic prosperity while effectively reducing global emissions. Finally *(iii)*, we consider whether industrial leakage is an unambigous by-product of asymmetric environmental policies.

To this aim, we need to introduce the following definition on *equilibrium dominance*:

Definition 3. The SK equilibrium
(i) **payoff dominates** the SM equilibrium whenever $G^*_{i,SK} \geq G^*_{i,SM}$, $\forall i = 1, 2$
(ii) **world emissions dominates** the SM equilibrium whenever the equilibrium world emissions are lower in the SK game than in the SM game, i.e. $P^*_{SK} < P^*_{SM}$
(iii) **dominates** the SM equilibrium when (i) **and** (ii) are verified.

From the above definition, we can state that if there exists a set of parameters such that the SK equilibrium *payoff dominates* the SM equilibrium, then both countries are better off when the industrialized country takes the lead. Additionally, in terms of global emissions, we can assert that if there is a set of parameters where global emissions are lower in the SK equilibrium compared to the SM equilibrium, the SK equilibrium is emissions dominant.

Finally, we assess whether leadership can result in an equilibrium that is not only payoff-dominant for both countries but also leads to a reduction in global emissions, making it emissions-dominant as well. If so, the SK equilibrium dominate and industralized countries' leadership in pollution mitigation is worthwile.
We can prove the following:

Proposition 1. *There exist a set of $\Delta c-$parameters such that the SK equilibrium dominates the SM equilibrium resulting in both the more industrialized and less industrialized countries being better off while also achieving lower global emissions.*

Proof. See Appendix 6.4.

□

The above proposition gives an insight on the effect that taking the lead may have on countries and world emissions. Contrary to the common wisdom pushed forward by the more industrialized countries, both countries may benefit from a sequential game. Moreover, and even more interestingly, there are circumstances such that the SK equilibrium is not only payoff dominant but also world emissions dominant so that it can reconcile two apparently conflicting goals: national payoff and world emissions abatement.

It is worth noting that, for the sake of generality, the above result has been proved without any restricting assumption on x_k^*, $k = SM, SK$, i.e. we solved the equilibrium analysis with $x_k^* \gtreqless 0$. Said differently, our result shows that

Corollary 2. *Even in presence of industrial leakage ($x_k^* > 0$), for some $\Delta c-$parameters, the more industrialized country is not penalized when taking the lead in emission abatement.*

This suggests that leading on environmental policy can still result in favorable outcomes for the advanced country, despite potential firm relocation. Manipulating the tax on profit enables the country to preserve its national payoff in spite of an outflow of firms. Also, industrial leakage in the sequential game does not always raise world emissions compared with a simultaneous game. *A priori*, industrial leakage is bad for the environment since due to the laxer environmental policies adopted by the less advanced countries. Moreover, the asymmetry in environmental policies is larger in the sequential than in the simultaneous game. However, equilibrium taxes can increase industrial leakage in the simultaneous (SM) game compared to the sequential (SK) game. As a result, world emissions may be lower in the SK scenario, despite the potential for firm relocation.[16] Note that even in a very specific case where a sequential game generates an industrial leakage while a simultaneous game generates an opposite flow of firms (from 2 to 1), it can exist a set of parameters that leads the SK equilibrium to be payoff and world emissions dominant (see example in Appendix 6.6). This outcome can occur when there are small asymmetries between the countries (in terms of the tolerance gap and manufacturing costs) and high relocation costs, leading to very weak industrial leakage. In this case, the benefit of a less stringent regulation policy in the industrialized country under the sequential (SK) game, compared to the simultaneous (SM) game, outweighs all other effects, resulting in lower overall emissions.[17]

[16]A suffisant condition ensuring a lower level of world emissions under the sequential game is that the industrial leackage is lower under the sequential game than under the simultaneous game (see Appendix 6.5).

[17]In order to gain some economic insights on the circumstances where the SK equilibrium is dominant with $x_k^* > 0$, we prove in Appendix that at the equilibrium, an outflow of firms from country 1 to country 2 is observed for a cost asymmetry such that $\Delta c > [\max[\Delta c_S^+, \Delta c_{SM}^+]$. The proofs for the other alternatives, i.e, 1) $x_k^* < 0$ for $k = SM, SK$, 2) $x_{SM}^* > 0$ and $x_{SK}^* < 0$, and, 3) $x_{SM}^* < 0$ and $x_{SK}^* > 0$ are available in an online Appendix. In each alternative, there exists a set of Δc-parameter such that a SK equilibrium dominance exists.

Table 1 illustrates the $\Delta c-$ parameters for which the SK equilibrium guarantees the payoff dominance and the world emissions dominance.

	Conditions on Δc	
$t_{1,SK} > 0$ and $t_{1,SM} > 0$ $t_{2,SK} > 0$ and $t_{2,SM} > 0$	$\Delta c \in [\max[\Delta c_{t_2SM}, \Delta c_{t_2SK}], \min[\Delta c_{t_1SM}, \Delta c_{t_1SK}]]$	
$x^*_{SK} > 0$ and $x^*_{SM} > 0$	$\Delta c > max[\Delta c^+_{SM}, \Delta c^+_{SK}]$	
Equilibrium area	$I_{TX} = \left\{\max[\Delta c_{t_2SM}, \Delta c_{t_2SK}, \Delta c^+_{SM}, \Delta c^+_{SK}], \min[\Delta c_{t_1SM}, \Delta c_{t_1SK}]\right\}$	
	SK Equilibrium Dominance	
$G_{1,SK} > G_{1,SM}$	$\Delta c < \Delta c^+_{1,min}$ or $\Delta c > \Delta c_{1,max}$	
$G_{2,SK} > G_{2,SM}$	$\Delta c^+_{2,min} < \Delta c < \Delta c^+_{2,max}$	
$P^*_{SM} > P^*_{SK}$	$\Delta c > \Delta c^+_P$ for $\bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\phi_1$	$\Delta c < \Delta c^+_P$ for $\bar{\alpha}_2 - \bar{\alpha}_1 < 3\gamma\phi_1$

Table 1: SK equilibrium dominance conditions with industrial leackage

It is interesting to notice that the condition on Δc ensuring that the SK equilibrium world emissions dominates the SM equilibrium changes depending on the level of *status quo* tolerance asymmetry ($\bar{\alpha}_2 - \bar{\alpha}_1$).

In particular, we find that:

- For a high *low status quo* tolerance asymmetry, i.e. $\bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\phi_1$, the SK equilibrium world emissions dominates the SM equilibrium when cost asymmetry is sufficiently high, i.e. $\Delta c > \Delta c_P$;

- For a low *low status quo* tolerance asymmetry, i.e. $\bar{\alpha}_2 - \bar{\alpha}_1 \leq 3\gamma\phi_1$, the SK equilibrium world emission dominates the SM equilibrium when cost asymmetry is low, i.e. $\Delta c \leq \Delta c_P$.

Thus,

Remark 1. *When the industrialized country takes the lead in emission abatement, world emissions decrease compared to a simultaneous setting under the following conditions: (i) Whenever both countries are relatively similar in terms of status quo emissions tolerance and production costs, or (ii) Whenever the countries are fundamentally different in these aspects, with significant disparities in their tolerance levels and production costs.*

In both cases, the leadership in abatement by the industrialized country leads to more effective global emissions reduction than simultaneous policy-setting. Specifically, when the *status quo* tolerance gap between the countries is large, world emissions are lower at the sequential (SK) equilibrium if the number of firms in country 1 at the SK equilibrium is higher than at the simultaneous (SM) equilibrium. Conversely, if the number of firms in country 1 is lower at the SK equilibrium compared to the SM equilibrium, the large *status quo* tolerance gap exacerbates world emissions at the SK equilibrium relative to the SM equilibrium. This holds for a sufficienlty high Δc.

Combining the conditions in Table 1 leads the following result (See Appendix 6.5 for more details):

- For $\bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\phi_1$,
  the SK equilibrium is dominant for $\Delta c \in [\max[\Delta c_P, \Delta c_{2,min}], \min[\Delta c_{1,min}, \Delta c_{2,max}]] \cap \; I_{TX}$
- For $\bar{\alpha}_2 - \bar{\alpha}_1 < 3\gamma\phi_1$,
  the SK equilibrium is dominant for $\Delta c \in [\Delta c_{2,min}, \min[\Delta c_{1,min}, \Delta c_{2,max}]] \cap \; I_{TX}$

Remark 2. *For a low status quo tolerance asymmetry, the equilibrium dominance is determined solely by payoff dominance.*

The *status quo* tolerance gap limits the industrial leakage or the inflow of firms from 2 to 1. It is bad for environment due to the more stringent environmental policy in country 1. This effect is even stronger in the SM equilibrum than in the SK equilibrium. If there is no difference in the *status quo* tolerance indices, the environmental policies in both countries are the same in SM, while the environmental policy in country 1 is more stringent in SK and even more stringent than in SM. As a result, global emissions are lower in the SK equilibrium (see Appendix 6.5 for a mathematical proof). This result remains valid for a low status quo tolerance gap.

The Figure 1 illustrates the previous remark.[18]

The triangle defines the possible equilibria with $x_k^* > 0$ for $k = SM, SK$. The darker zone shows the area where the SK equilibrium dominates the SM equilibrium. In the lighter zone, the SK equilbium remains world emissions dominant but no longer payoff dominant. In the white zone, none of the dominance condition apply. In this example, Figure 1 shows that the zone where the SK is not dominant corresponds to small tolerance asymmetry and a fairly low manufacturing cost differential as specified in Remark 1. Also, as noted in Remark 2, the set of parameters that allow global emissions to be lower in the SK equilibrium includes the set of parameters that allow payoff dominance.

Remark 3. *When $D_i = \gamma E_i$ so that countries are only concerned with local emissions, it does not exist a SK equilibrium that is dominant: countries payoffs and world environmental issues are always in conflict.*

[18]The graph is drawn for the parameter values $\gamma = 0.5$, $\overline{\alpha}_2 = 1$, $\phi_1 = 0.2$, $\phi_2 = 0.5$, $k = 0.5$, $q = 10$ and $s_1 = 0.75$.

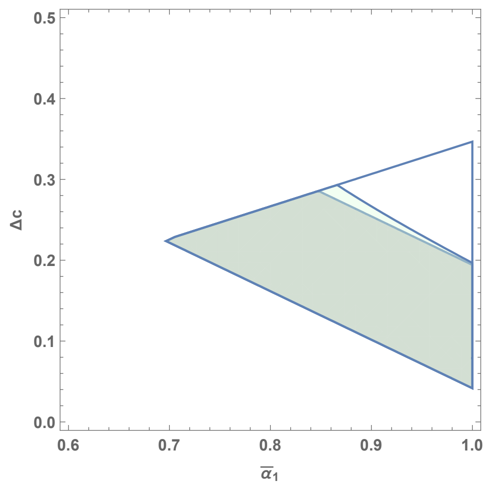

Figure 1: Industrial leakage: $x^*_{SM} > 0$ and $x^*_{SK} > 0$

Proof. For $\phi_1 = 0$ and $\phi_2 = 0$, $\Delta c_{1,min} = \Delta c_{1,max}$ so that country 1 is always better off at SK equilibrium than at the SM equilibrium (Proof of Lemma 3). Moreover, $\Delta c_{1,min} = \Delta c_{1,max} = \Delta c_{2,max} = \Delta c_P$. Since $G^*_{2,SK} \geq G^*_{2,SM} \iff \Delta c_{2,\max} > \Delta c > \Delta c_{2,\min}$ and $P_{SM} > P_{SK} \iff \Delta c > \Delta c_P$, we cannot have simultaneously $G^*_{2,SK} \geq G^*_{2,SM}$ and $P_{SM} > P_{SK}$. □

When governments focus exclusively on local pollution, the first-mover advantage is fully realized, but so is the second-mover disadvantage. The lack of consideration for transboundary emissions in the governments' objectives results in similar environmental regulations for country 1, regardless of whether the game is simultaneous or sequential. This situation is detrimental to the environment. As a result, in the sequential game, the less industrialized country's situation cannot improve without a corresponding increase in global emissions, and *vice versa*.

The above remark opens the door to a further policy consideration. Pollution is a global phenomenon and has to be treated as such: neglecting transboudary emissions prevents government from reaching the twofold scope of preserving national payoff and saving the planet.

5 Conclusion

The debate between the more and the less industrialised countries on the responsibilities for curbing emissions is still open. Contrary to the well-known view that the leader has a first mover advantage in a Stackelberg game, the more industrialized countries complain about the leading position attributed to them in international negotiations. In this paper, we have investigated the economic rationale behind their complaints and we have considered whether a different timing of policies could contribute to curbing global emissions without without disadvantaging the more industrialized countries. We have shown that the arguments against the CBDR principle are not well–founded. In the more realistic case of industrial leackage, which is feared by the more industrialized countries, there is a wide range of situations where national targets and global emissions reductions can be reconciled. However, this outcome depends on countries addressing transboundary pollution as well as local pollution.

6 Appendix

6.1 SM and SK equilibria

Remind that

$$R_i = N_i t_i \tag{9}$$

$$E_i = q\alpha_i N_i \tag{10}$$

with

$$\begin{aligned}
\frac{\partial N_i}{\partial t_i} &= -\frac{\partial N_j}{\partial t_i} = -\frac{s_k}{k} \\
\frac{\partial N_i}{\partial \alpha_i} &= -\frac{\partial N_j}{\partial \alpha_i} = q\frac{s_k}{k}(1-\alpha_i)
\end{aligned}$$

where $s_k = s_1$ when $x > 0$ and $s_k = 1 - s_1$ when $x < 0$. Thus

$$\frac{\partial N_i}{\partial \alpha_i} = -q(\bar{\alpha}_i - \alpha_i)\frac{\partial N_i}{\partial t_i} \tag{11}$$

Simultaneous game

The first order conditions gives the following

$$\begin{aligned}
\frac{\partial G_i}{\partial t_i} = \frac{\partial R_i}{\partial t_i} - \gamma\left(\frac{\partial E_i}{\partial t_i} + \phi_j\frac{\partial E_j}{\partial t_i}\right) = 0 \\
\frac{\partial G_i}{\partial \alpha_i} = \frac{\partial R_i}{\partial \alpha_i} - \gamma\left(\frac{\partial E_i}{\partial \alpha_i} + \phi_j\frac{\partial E_j}{\partial \alpha_i}\right) = 0
\end{aligned}$$

Using (9), (10) and (11), we can write

$$\begin{aligned}
\frac{\partial G_i}{\partial t_i} &= \frac{\partial N_i}{\partial t_i}(t_i - \gamma q(\alpha_i - \phi_j\alpha_j)) + N_i = 0 \\
&= -\frac{s_k}{k}(t_i - \gamma q(\alpha_i - \phi_j\alpha_j)) + N_i = 0 \qquad (12)
\end{aligned}$$

With

$$\frac{\partial^2 G_i}{\partial t_i^2} = -2\frac{s_k}{k} < 0$$

which guarantees that the SOC is satisfied.

$$\frac{\partial R_i}{\partial \alpha_i} = q(\bar{\alpha}_i - \alpha_i)\left(N_i - \frac{\partial R_i}{\partial t_i}\right)$$

$$\frac{\partial E_i}{\partial \alpha_i} = q\left(N_i - (\bar{\alpha}_i - \alpha_i)\frac{\partial E_i}{\partial t_i}\right)$$

$$\frac{\partial E_j}{\partial \alpha_i} = -q\left((\bar{\alpha}_i - \alpha_i)\frac{\partial E_j}{\partial t_i}\right)$$

Thus

$$\begin{aligned}
\frac{\partial G_i}{\partial \alpha_i} &= \frac{\partial R_i}{\partial \alpha_i} - \gamma\left(\frac{\partial E_i}{\partial \alpha_i} + \phi_i\frac{\partial E_j}{\partial \alpha_i}\right) \\
&= q(\bar{\alpha}_i - \alpha_i)\left(N_i - \frac{\partial R_i}{\partial t_i}\right) - \gamma\left(q\left(N_i - (\bar{\alpha}_i - \alpha_i)\frac{\partial E_i}{\partial t_i}\right) - \phi_i q(\bar{\alpha}_i - \alpha_i)\frac{\partial E_j}{\partial t_i}\right) \\
&= \underbrace{-q(\bar{\alpha}_i - \alpha_i)\left(\frac{\partial R_i}{\partial t_i} - \gamma\left(\frac{\partial E_i}{\partial t_i} + \phi_i\frac{\partial E_j}{\partial t_i}\right)\right)}_{=0} + q(\bar{\alpha}_i - \alpha_i)N_i + \gamma q N_i
\end{aligned}$$

Then

$$\frac{\partial G_i}{\partial \alpha_i} = 0 \iff \gamma = (\bar{\alpha}_i - \alpha_i)$$

Sequential game

At the sequential game, the FOC of the simultaneous game remain for country 2.

$$\begin{aligned}
\frac{\partial G_1}{\partial t_1} = \frac{\partial R_1}{\partial t_1} + \frac{\partial R_1}{\partial t_2}\frac{\partial t_2}{\partial t_1} - \gamma\left(\frac{\partial E_1}{\partial t_1} + \phi_2\frac{\partial E_2}{\partial t_1}\right) - \gamma\left(\frac{\partial E_1}{\partial t_2} + \phi_2\frac{\partial E_2}{\partial t_2}\right)\frac{\partial t_2}{\partial t_1} = 0 \\
\frac{\partial G_1}{\partial \alpha_1} = \frac{\partial R_1}{\partial \alpha_1} + \frac{\partial R_1}{\partial t_2}\frac{\partial t_2}{\partial \alpha_1} - \gamma\left(\frac{\partial E_1}{\partial \alpha_1} + \phi_2\frac{\partial E_2}{\partial \alpha_1}\right) - \gamma\left(\frac{\partial E_1}{\partial t_2} + \phi_2\frac{\partial E_2}{\partial t_2}\right)\frac{\partial t_2}{\partial \alpha_1} = 0
\end{aligned} \tag{13}$$

with

$$\frac{\partial t_2}{\partial t_1} = \frac{1}{2}$$

and

$$\frac{\partial t_2}{\partial \alpha_1} = -\frac{1}{2}q\left(\bar{\alpha}_1 - \alpha_1 + \gamma\phi_1\right)$$

from (12)

It results

$$\frac{\partial G_1}{\partial t_1} = N_1 - \frac{1}{2}\frac{s_k}{k}t_1 + \frac{q\gamma}{2}\frac{s_k}{k}(\alpha_1 - \phi_2\alpha_2)) = 0 \tag{14}$$

With

$$\frac{\partial^2 G_i}{\partial t_i^2} = -\frac{s_k}{k} < 0$$

which satisfies the SOC, and

$$\begin{aligned}
\frac{\partial G_1}{\partial \alpha_1} = \quad & \underbrace{q(\bar{\alpha}_1 - \alpha_1)\left(\frac{\partial R_1}{\partial t_1} + \frac{\partial R_1}{\partial t_2}\frac{\partial t_2}{\partial t_1} - \gamma\left(\frac{\partial E_1}{\partial t_1} + \phi_2\frac{\partial E_2}{\partial t_1}\right) - \gamma\left(\frac{\partial E_1}{\partial t_2} + \phi_2\frac{\partial E_2}{\partial t_2}\right)\frac{\partial t_2}{\partial t_1}\right)}_{=0 \text{ from (13)}} \\
& + qN_1(\bar{\alpha}_1 - \alpha_1 - \gamma) - \gamma q\phi_1 \underbrace{\left(\frac{1}{2}\frac{s_k}{k}t_{-} \frac{q\gamma}{2}\frac{s_k}{k}(\alpha_1 - \phi_2\alpha_2)\right)}_{=N_1 \text{ from (14)}} = 0
\end{aligned}$$

Then

$$\frac{\partial G_1}{\partial \alpha_1} = 0 \iff \gamma = (\bar{\alpha}_1 - \alpha_1 - \gamma\phi_1)$$

6.2 Conditions on taxes

At the simultaneous game, positive taxes imply $\Delta c_{t_2 SM} < \Delta c < \Delta c_{t_1 SM}$ with

$$\begin{aligned}
\Delta c_{t_1 SM} &= \frac{k(1+s_1)}{qs_i} + \gamma\left((\bar{\alpha}_1 - \gamma)(1-\phi_1) + 2(\bar{\alpha}_2 - \gamma)(1-\phi_2) - (\bar{\alpha}_2 - \bar{\alpha}_1)\right) \\
\Delta c_{t_2 SM} &= -\frac{k(1+s_2)}{qs_i} - \gamma\left((\bar{\alpha}_2 - \gamma)(1-\phi_2) + 2(\bar{\alpha}_1 - \gamma)(1-\phi_1) + (\bar{\alpha}_2 - \bar{\alpha}_1)\right) < 0
\end{aligned}$$

At the sequential game, positive taxes imply $\Delta c_{t_2 SK} < \Delta c < \Delta c_{t_1 SK}$ with

$$\begin{aligned}
\Delta c_{t_1 SK} &= \frac{k(1+s_1)}{qs_i} + \gamma\left(\bar{\alpha}_2(1-\phi_2) + \bar{\alpha}_1(1-\phi_1) + \gamma(\phi_2 - \phi_1) - 2\gamma + \frac{1}{2}\gamma\phi_1^2\right) \\
\Delta c_{t_2 SK} &= -\frac{k(2+s_2)}{qs_i} - \gamma\left(\bar{\alpha}_1(1-3\phi_1) + \bar{\alpha}_2(3-\phi_2) + \gamma(3\phi_1 + \phi_2) - 4\gamma + \frac{7}{2}\gamma\phi_1^2\right)
\end{aligned}$$

with $s_i = s_1$ when $x^* > 0$, and $s_i = s_2$ when $x^* < 0$. Then, we restrict our analysis to the following interval for parameter Δc: $I_T = [\max[\Delta c_{t_2 SM}, \Delta c_{t_2 SK}], \min[\Delta c_{t_1 SM}, \Delta c_{t_1 SK}]]$.

6.3 Payoffs and world emissions

The expressions of the payoff are obtained by Mathematica. Programs are available upon request.

$$\begin{aligned}
G^*_{1,SM} &= \frac{1}{9}\left(\frac{q^2(s_i\left(\bar{\alpha}_1\gamma(\phi_1+1) - \bar{\alpha}_2\gamma(\phi_2+1) + \gamma^2(\phi_2 - \phi_1) + \Delta c\right)^2}{k} + \frac{k(s_1+1)^2}{s_i}\right. \\
&- q\left(-2\gamma^2\phi_1 - 7\gamma^2\phi_2 + 2\Delta c + 2\bar{\alpha}_1\gamma(s_1+1)(\phi_1+1) - \bar{\alpha}_2\gamma(2s_1(\phi_2+1) - 7\phi_2 + 2)\right. \\
&- \left.\left. 2\gamma^2 s_1\phi_1 + 2\gamma^2 s_1\phi_2 + 2\Delta c s_1\right)\right)
\end{aligned}$$

$$
\begin{aligned}
G^*_{1,SK} &= \frac{1}{32}\Bigg(\frac{q^2 s_i\left(-2\bar{\alpha}_1\gamma(\phi_1+1)+2\bar{\alpha}_2\gamma(\phi_2+1)+\gamma^2\phi_1^2+2\gamma^2(\phi_1-\phi_2)-2\Delta c\right)^2}{k}+\frac{4k(s_1+1)^2}{s_i}\\
&- 4q\left(-\gamma^2\phi_1^2-2\gamma^2\phi_1-6\gamma^2\phi_2+2\Delta c+2\bar{\alpha}_1\gamma(s_1+1)(\phi_1+1)-2\bar{\alpha}_2\gamma(s_1\phi_2+s_1-3\phi_2+1)\right.\\
&- \left.\gamma^2 s_1\phi_1^2-2\gamma^2 s_1\phi_1+\ 2\gamma^2 s_1\phi_2+2\Delta c s_1\right)\Bigg)
\end{aligned}
$$

$$
\begin{aligned}
G^*_{2,SM} &= \frac{1}{9}\Bigg(\frac{q^2 s_i\left(\bar{\alpha}_1\gamma(\phi_1+1)-\bar{\alpha}_2\gamma(\phi_2+1)+\gamma^2(\phi_2-\phi_1)+\Delta c\right)^2}{k}+\frac{k(1+s_2)^2}{s_i}\\
&+ q\left(5\gamma^2\phi_1+4\gamma^2\phi_2+4\Delta c-\bar{\alpha}_1\gamma(2s_1(\phi_1+1)+5\phi_1-4)+2\bar{\alpha}_2\gamma(s_1-2)(\phi_2+1)\right.\\
&+ \left.2\gamma^2 s_1\phi_1-2\gamma^2 s_1\phi_2-2\Delta c s_1\right)\Bigg)
\end{aligned}
$$

$$
\begin{aligned}
G^*_{2,SK} &= \frac{1}{64}\Bigg(\frac{q^2 s_i\left(-2\bar{\alpha}_1\gamma(\phi_1+1)+2\bar{\alpha}_2\gamma(\phi_2+1)+\gamma^2\phi_1^2+2\gamma^2(\phi_1-\phi_2)-2\Delta c\right)^2}{k}+\frac{4k(2+s_2)^2}{s_i}\\
&- 4q\left(-13\gamma^2\phi_1^2-10\gamma^2\phi_1-6\gamma^2\phi_2-6\Delta c+2\bar{\alpha}_1\gamma(s_1\phi_1+s_1+5\phi_1-3)\right.\\
&- \left.2\bar{\alpha}_2\gamma(s_1-3)(\phi_2+1)-\gamma^2 s_1\phi_1^2-2\gamma^2 s_1\phi_1+2\gamma^2 s_1\phi_2+2\Delta c s_1\right)\Bigg)
\end{aligned}
$$

with $s_i = s_1$ when $x^* > 0$, and $s_i = s_2$ when $x^* < 0$.

6.4 Proof of Proposition 1

Here, we assume that the flow of firms moves in the same direction regardless of the type of game, whether simultaneous or sequential, which means, either $x_{SM} > 0$ and $x_S > 0$ or $x_{SM} < 0$ and $x_S < 0$. The alternative cases are available in the online Appendix.[19]

Payoff dominance:

$$G^*_{1,SK} \geq G^*_{1,SM} \Leftrightarrow \Delta c \leq \Delta c_{1,\min} \text{ or } \Delta c \geq \Delta c_{1,\max}.$$

with

$$
\begin{aligned}
\Delta c_{1,\max} &\equiv \Gamma+\frac{k(1+s_1)}{qs_i}+\frac{\gamma^2}{2}(9+6\sqrt{2})\phi_1^2\\
\Delta c_{1,\min} &\equiv \Gamma+\frac{k(1+s_1)}{qs_i}+\frac{\gamma^2}{2}(9-6\sqrt{2})\phi_1^2
\end{aligned}
$$

[19]The expressions are obtained by Mathematica. Programs are available upon request.

with

$$\Gamma = \gamma\left((\bar{\alpha}_2 - \bar{\alpha}_1) - \phi_1(\bar{\alpha}_1 - \gamma) + \phi_2(\bar{\alpha}_2 - \gamma)\right)$$

Also,

$$G^*_{2,SK} \geq G^*_{2,SM} \Leftrightarrow \Delta c \in [\Delta c_{2,\min}, \Delta c_{2,\max}]$$

with

$$\begin{aligned} \Delta c_{2,\min} &= \Delta c_2 - \eta \\ \Delta c_{2,\max} &= \Delta c_2 + \eta \end{aligned}$$

where

$$\Delta c_2 \equiv \Gamma - \frac{7ks_1 - 5}{7qs_i} - \frac{9}{14}\gamma^2\phi_1^2$$

and

$$\eta \equiv \frac{6}{7qs_i}\sqrt{4k^2 + 24kqs_i\gamma^2\phi_1^2 + q^2s_i^2\gamma^4\phi_1^4},$$

World emissions dominance

$$P_{SM} = \frac{qk(\bar{\alpha}_1(1+s_1) + \bar{\alpha}_2(1+s_2) - 3\gamma) - q^2s_i(\bar{\alpha}_1 - \bar{\alpha}_2)\left(\bar{\alpha}_1\gamma(\phi_1+1) - \bar{\alpha}_2\gamma(\phi_2+1) + \gamma^2(\phi_2-\phi_1) + \Delta c\right)}{3k}$$

$$P_{SK} = \frac{q\left(2k(\bar{\alpha}_1(s_1+1) + \bar{\alpha}_2(2+s_2) - \gamma(s_1\phi_1 + \phi_1 + 4)\right)}{8k} - \frac{q^2s_i(\bar{\alpha}_1 - \bar{\alpha}_2 - \gamma\phi_1)\left(2\bar{\alpha}_1\gamma(\phi_1+1) - 2\bar{\alpha}_2\gamma(\phi_2+1) - \gamma^2\phi_1^2 + 2\gamma^2(\phi_2-\phi_1) + 2\Delta c\right.}{8k}$$

$$P_{SM} > P_{SK} \Longleftrightarrow \begin{cases} \Delta c > \Delta c_P & \text{for} \quad \bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\phi_1 = \Delta\bar{\alpha}_\gamma \\ \Delta c < \Delta c_P & \text{otherwise} \end{cases}$$

with

$$\Delta c_P \equiv \Gamma + \frac{k(1+s_1)}{qs_i} + \frac{3\gamma^3\phi_1^2(\bar{\alpha}_2 - \bar{\alpha}_1 + \gamma\phi_1)}{2(3\gamma\phi_1 - (\bar{\alpha}_2 - \bar{\alpha}_1))}$$

We immediately deduce

$$\Delta c_{1,\max} > \Delta c_{2,\max}$$

$$\Delta c_{1,\min} > \Delta c_{2,\min}$$

Equilibrium dominance

Thus, an equilibrium is payoff and world emissions dominant if $\Delta c \in I_{SK} \cap I_T$ (See Appendix 6.2 for I_T) with

$$I_{SK} = \begin{cases} [\max\{\Delta c_{2,min}, \Delta c_P\}, \min\{\Delta c_{1,min}, \Delta c_{2,max}\}] & \text{for} \quad \bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\phi_1 \\ [\Delta c_{2,min}, \min\{\Delta c_{1,min}, \Delta c_{2,max}, \Delta c_P\}] & \text{for} \quad \bar{\alpha}_2 - \bar{\alpha}_1 < 3\gamma\phi_1 \end{cases}$$

6.5 Industrial leakage

6.5.1 Sufficient condition for $P_{SK} < P_{SM}$

Global pollution is given by $P = N_1\alpha_1 + N_2\alpha_2$. Thus,

$$P_{SM} > P_{SK} \iff N_{1,SM}\alpha_{1,SM} + N_{2,SM}\alpha_{2,SM} > N_{1,SK}\alpha_{1,SK} + N_{2,SK}\alpha_{2,SK}$$

As $\alpha_{2,SM} = \alpha_{2,SK}$, $\alpha_{2,SK} = \alpha_{2,SM} - \gamma\phi_1$ and $N_1 + N_2 = 1$, this is equivalent to

$$P_{SM} > P_{SK} \iff (N_{1,SK} - N_{1,SM})(\alpha_{2,SM} - \alpha_{1,SM}) + N_{1,SK}\gamma\phi_1 > 0$$

and since $\alpha_{2,SM} > \alpha_{1,SM}$ a sufficient condition for $P_{SK} < P_{SM}$ is $N_{1,SK} > N_{1,SM}$.

6.5.2 Thresholds of manufacturing cost differentials in case of industrial leakage

Let us consider cases where $x_{SM} > 0$ and $x_{SK} > 0$. This implies $s_i = s_1$ for values of x and the thresholds of Δc. Also, $x^* > 0$ implies

$$\Delta c > \max[\Delta c^+_{SM}, \Delta c^+_{SK}]$$

with

$$\Delta c^+_{SM} = \Gamma - \frac{k(s_1 - s_2)}{qs_1}$$

and

$$\Delta c^+_{SK} = \Gamma + \frac{\gamma^2}{2}\phi_1^2 - \frac{k(2s_1 - s_2)}{qs_1}$$

The interval on which the equilibrium is defined with industrialized leakage in both games is thus

$$I_{TX} = \left\{\max[\Delta c_{t_2SM}, \Delta c_{t_2SK}, \Delta c^+_{SM}, \Delta c^+_{SK}], \min[\Delta c_{t_1SM}, \Delta c_{t_1SK}]\right\}$$

Also, the ranking of $\Delta c_{1,\max}$ and $\Delta c_{2,\min}$ and Δc_P with the other thresholds gives the following results :

$$\Delta c_{1,\min} > \Delta c_{2,\max} \iff q > \frac{4(24+17\sqrt{2})k}{\gamma^2\phi_1^2 s_1}$$

and

For $\bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\Phi_1$; $\Delta c_{2,max} > \Delta c_P$ and $\Delta c_{1,min} > \Delta c_P$

For $\bar{\alpha}_2 - \bar{\alpha}_1 < 3\gamma\Phi_1$; $\Delta c_P > \Delta c_{2,min}$, $\Delta c_P > \Delta c_{1,min}$ and

$$\Delta c_P < \Delta c_{1,max} \iff \bar{\alpha}_2 - \bar{\alpha}_1 < \frac{4+3\sqrt{(2)}}{2+2\sqrt{(2)}}\gamma\phi_1 \text{ (with} 4+3\sqrt{2}2+2\sqrt{2} \equiv 1.71)$$

Conclusion:

For $\bar{\alpha}_2 - \bar{\alpha}_1 > 3\gamma\Phi_1$,the SK equilibrium is payoff and environment dominant for $\Delta c \in [\max[\Delta c_P, \Delta c_{2,min}], \min[\Delta c_{1,min}, \Delta c_{2,max}]] \cap I_{TX}$

For $\bar{\alpha}_2 - \bar{\alpha}_1 < 3\gamma\Phi_1$, the SK equilibrium is payoff and environment dominant for $\Delta c \in [\max[\Delta c_{2,min}], \min[\Delta c_{1,min}, \Delta c_{2,max}]] \cap I_{TX}$.

6.6 Illustration for $x^*_{SK} > 0$ and $x^*_{SM} < 0$

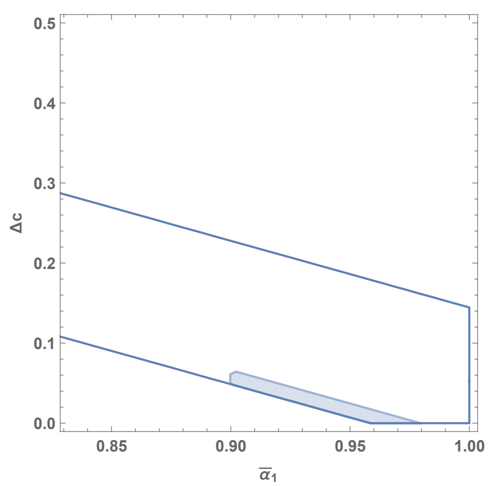

Figure 2: $x^*_{SK} > 0$ and $x^*_{SM} < 0$

The graph is drawn for the parameter values $\gamma = 0.8$, $\overline{\alpha}_2 = 1$, $\phi_1 = 0.04$, $\phi_2 = 0.99$, $k = 0.9$, $q = 5$ and $s_1 = 0.51$. The white area defined by blue lines represents the set of parameters allowing for equilibrium existence. The blue zone characterizes the zone where the SK equilibrium is both payoff and wolrd emission dominant.

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