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GHG Emissions, Lobbying, Free-Riding, and Technological Change

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Abstract

This document examines GHG emission policy in a world where labor and emissions are complementary in production, world-wide emissions decrease welfare, and total factor productivity can be locally improved by devoting labor to R&D. A subset of the countries can establish an "abatement coalition" where an international agency grants non-traded or traded GHG permits. This agency is self-interested, subject to lobbying, and has no budget of its own. The results are the following. The establishment of the ``abatement coalition" enhances welfare, promotes economic growth and diminishes emissions both inside and outside the coalition. Without technological change, emission permit trade does not make any difference. With technological change due to R&D, the agreement with emission permit trade is Pareto worsening.

JEL Classification: 041, H23, F15, Q53

Keywords: GHG emissions, technological change, lobbying.

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1 Introduction

This document considers two issues of emission policy: (*i*) If some countries limit their GHG emissions, then how do the other "free-riding" countries respond to this? (*ii*) How much authority should the GHG-limiting countries delegate to an international agency that coordinates their actions?

The EU has been willing to act as a leader of international climate policy (Oberthür 2009; Vogler 2005). However, because concerns over the competitiveness of the EU and the political influence of industry pressure groups have generated substantial concessions to the emitting sectors (Markussen and Svendsen 2005; Neuhoff et al. 2006), it is realistic to assume a non-benevolent policy maker. This document assumes that the international agency in a coalition of countries is self-interested and subject to lobbying.

In the literature, there are different results on free riding in emission policy depending on the structure of the model. Babiker (2005) shows in a multi-good model of international trade that the escape of dirty industries from a coalition of abating countries offsets emission reductions achieved within that coalition. In contrast, Grubb et al. (2002) and Di Maria and van der Werf (2008) show in a variety-expansion model of growth that local emission cuts spur GHG-saving innovations, generating emission cuts elsewhere.

Copeland and Taylor (2005) consider emission permit trading in a two-good two-factor model. They show that with the terms-of-trade effect, such trading may increase GHG emissions and make both trading partners worse off. This document ignores the terms-of-trade effect and assumes one internationally-tradable good, with quality ladders in technology.

Böringer and Lange (2005) derive optimal schemes for the free allocation of emission allowances in a dynamic context, but with no technological change. They consider emissions-based allocation rules which allow for updating of the basis of allocation over time.[1] They show that with an absolute

[1]Later on, Mackenzie et al. (2008) extend Böhringer and Lange's (2005) analysis to

cap on emissions, *grandfathering* schemes which allocate allowances proportionally to past emissions are first-best. This document considers grandfathering as well, but in the case where the emission cap is endogenously determined by negotiation between the countries and the international agency.

Haurie et al. (2006) construct the necessary optimality conditions for a negotiation game in the following situation: *(a)* There is an exogenous precise constraint on the accumulation of GHGs in the atmosphere. *(b)* An international agreement should be reached on the relative development paths of the different countries and their use of GHGs to foster their development. *(c)* GHG are used as a by-product in the economic production process, permitting the use of cheaper "dirty" technologies, but their abatement can also be used as a source of income in an international emissions trading system. *(d)* The agreement should be self-enforcing, i.e. there must be a noncooperative equilibrium of the strategic game between the countries.

This document assumes self-enforcing agreements, but departs from the other assumptions of Haurie et al. (2006) as follows: *(a),(b)* The constraint on global GHG emissions is endogenously determined by negotiation between the countries and the international agency. *(c)* GHG emissions are an *input*, not a by-product in the economic production process. With these modifications, one can examine the entire negotiation game starting from the determination of emission caps instead of a subgame of that starting from the imposition of emission caps.

Gersbach and Winkler (2011) propose a blueprint for an international emission permit market (e.g. the EU trading scheme) as follows. Each country decides on the amount of permits it wants to offer. A fraction of these permits is freely allocated, the remainder is auctioned. Revenues from the auction are collected in a global fund and reimbursed to member countries in fixed proportions. Gersbach and Winkler show that international per-

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a more general design of a dynamic initial allocation mechanism, which allows for the allocation of permits to be based on each firm's choices relative to other firms.

mit markets with refunding make all countries to tighten their issuance of permits, thereby increasing welfare in all countries. If the share of freely allocated permits is sufficiently small, socially optimal emission reductions can be obtained. In contrast to Gersbach and Winkler (2011), there is no refunding in the model of this document.

Caplan et al. (2003) show that an international policy scheme with emission permit trading, redistributive transfers and global participation yields an efficient allocation for a global economy. Their analysis is however based on the assumption of an altruistic international agency that operates the resource transfer mechanism. This document assumes a self-interested international agency that runs emission policy, has no direct transfer instruments and is subject to lobbying by the local governments.

Palokangas (2009) examines the implementation of emission policy with a self-interested international agency in a quality-ladders model of growth. That article shows that on fairly general conditions, emission trade speeds up growth from the initial position of laissez-faire, but slows down from the initial position of centrally-determined emission quotas. This document assumes that there are free riders, with different preferences and technology. In that framework, a simple grandfathering scheme of granting GHG permits is shown to be Pareto superior to using the traded GNG permits.

This document is organized as follows. Sections 2 presents the general structure of the economy. Section 3 examines free rider, Section 4 grandfathering and Section 5 trade in GHG permits, respectively.

2 The model

Let a great number of countries be placed evenly within the limit $[0, N]$. In each country $j \in [0, N]$, there is a representative agent (hereafter called *country* j) that has the full control of resources in that country. Labor and emissions are the primary factors of production. All countries possess one unit of labor which can be used in production or research and development (R&D). R&D improves total factor productivity (TFP) in the country.

The source of externality is that total emissions in all countries,

$$M = \int_0^N m_j dj. \tag{1}$$

hurt everybody in all countries. Subset $[0, n]$ of countries $[0, N]$ establishes an abatement coalition in which an *international agency* attempts to regulate GHG emissions. The agency is self-interested and subject to lobbying from the *member countries* $j \in [0, n]$. The remainder of countries, $j \in (n, N]$, are *free riders*. In this setting, two questions are posed:

(i) Is the agreement on the coalition self-enforcing, i.e. is there a noncooperative equilibrium of the strategic game between the member countries?

(ii) Should emission permit trade be introduced into the coalition?

2.1 Preferences

To simplify the model, this document eliminates

- the terms-of-trade effect by the assumption that there is only one consumption good in all countries, and
- international capital movements in equilibrium by the assumption that all countries share the same constant rate of time preference, ρ.

With these assumptions, the countries can grow at different rates in a stationary-state equilibrium.

Country j chooses its flow of consumption C_j to maximize its expected utility starting at time T,

$$E \int_T^\infty C_j M^{-\delta_j} e^{-\rho(\theta - T)} d\theta, \quad \delta_j > 0, \quad \rho > 0, \tag{2}$$

where E is the expectation operator, θ time, ρ the constant rate of time preference and δ_j a parameter. The higher δ_j, the more country j dislikes emissions M. Because there is no money that would pin down the nominal prices in the model, the consumption price can be normalized P at $M^{-\delta}$:

$$P = M^{-\delta}. \tag{3}$$

2.2 Production

Country j devotes the amount l_j of its labor to production and the rest

$$z_j = 1 - l_j \tag{4}$$

to R&D. It produces the consumption good from labor l_j and emissions m_j, but improves its TFP through its R&D.

When country j develops a new technology, it increases its total factor productivity (TFP) by constant $a > 1$. Its TFP is then equal to a^{γ_j}, where γ_j is its serial number of technology. Given TFP, country j is subject to the CES production function $f^j(l_j, m_j)$, where l_j (m_j) is the input of labor (emissions). Thus, it produces the consumption good according to

$$Y_j = a^{\gamma_j} f^j(l_j, m_j). \tag{5}$$

This document makes the plausible assumption that labor l_j and emissions m_j are gross complements, i.e. the elasticity of substitution between them is less than one. This means that an increase in the relative use of emissions, m_j/l_j, decreases the value-added proportion of emissions, ξ_j:

$$\begin{aligned} \frac{m_j f_n^j(l_j, m_j)}{f^j(l_j, m_j)} &= \frac{f_n^j(l_j/m_j, 1)}{f^j(l_j/m_j, 1)} \doteq \xi_j\left(\frac{l_j}{m_j}\right), \quad \xi_j' > 0, \\ \frac{l_j f_l^j(l_j, m_j)}{f^j(l_j, m_j)} &= 1 - \xi_j\left(\frac{l_j}{m_j}\right), \quad f_l^j \doteq \frac{\partial f}{\partial l_j}, \quad f_n^j \doteq \frac{\partial f^j}{\partial m_j}. \end{aligned} \tag{6}$$

2.3 Research and development (R&D)

The improvement of technology in country j depends on labor devoted to R&D in that country, z_j. In a small period of time $d\theta$, the probability that

R&D leads to development of a new technology with a jump from γ_j to γ_j+1 is given by $\lambda z_j d\theta$, while the probability that R&D remains without success is given by $1-\lambda z_j d\theta$, where λ is productivity in R&D. Noting (4), this defines a Poisson process χ_j with

$$d\chi_j = \begin{cases} 1 & \text{with probability } \lambda z_j d\theta = \lambda(1-l_j)d\theta, \\ 0 & \text{with probability } 1-\lambda z_j d\theta = 1-\lambda(1-l_j)d\theta, \end{cases} \tag{7}$$

where $d\chi_j$ is the increment of the process χ_j. The expected growth rate of productivity a^{γ_j} in the production sector in the stationary state is given by

$$g_j \doteq E\big[\log\, a^{\gamma+1} - \log\, a^{\gamma}\big] = (\log a)\lambda z_j = (\log a)\lambda(1-l_j),$$

where E is the expectation operator (cf. Aghion and Howitt 1998, p. 59). Because the expected growth rate g_j of output in country j is in fixed proportion to z_j, then labor devoted to R&D in that country, $z_j = 1-l_j$, can be used as a proxy of growth in that country.

3 Free riders

3.1 Optimal program

Free-riding country $j \in (n,N]$ consumes what it produces, $C_j = Y_j$. It behaves in Cournot manner and takes emissions in the other countries

$$m_{-j} \doteq M - m_j = \int_{k\neq j} m_k dk \tag{8}$$

as given. Plugging $C_j = Y_j$, (5) and (8) into (2) and using the expectation operator E, one obtains its expected utility starting at time T as follows:

$$E\int_T^\infty C_j M^{-\delta_j} e^{-\rho(\theta-T)} d\theta = E\int_T^\infty Y_j M^{-\delta_j} e^{-\rho(\theta-T)} d\theta$$
$$= E\int_T^\infty \frac{a^{\gamma_j} f^j(l_j,m_j)}{(m_j+m_{-j})^{\delta_j}} e^{-\rho(\theta-T)} d\theta. \tag{9}$$

Country $j \in (n,N]$ maximizes its expected utility (9) by its emissions and labor in production, (m_j, l_j), subject to Poisson technological change (7), holding the emissions elsewhere, m_{-j}, constant. The solution is this optimal program is given by (cf. Appendix A)

$$\begin{aligned} & z_j(M) \text{ with } z_j' < 0 \text{ and } m_j(M) \text{ with } m_j' > 0 \text{ for } j \in (n, N], \\ & \int_n^N m_j' dj < \frac{1}{M} \int_n^N m_j dj < 1. \end{aligned} \tag{10}$$

Inserting (10) into (8) yields $M = m_j(M) + m_{-j}$. Differentiating this totally and noting (4) and (10), one obtains

$$\frac{dM}{dm_{-j}} = \frac{1}{1 - m_j'} > 0, \quad \frac{dm_j}{dm_{-j}} = m_j' \frac{dM}{dm_{-j}} > 0, \quad \frac{dz_j}{dm_{-j}} = z_j' \frac{dM}{dm_{-j}} < 0.$$

In other worlds:

Proposition 1 *Emission cuts elsewhere (i.e. a fall in m_{-j}) decrease a free rider's emissions, $dm_j/dm_{-j} > 0$, but promote its growth, $dz_j/dm_{-j} < 0$.*

3.2 Strategic complementarity

In the literature, a number of effects have been proposed to explain this strategic complementarity of emission policy:

- *Income effect.* An increase in the free riders' real income due to emission policy decreases emissions (e.g. Copeland and Taylor 2005).
- *Induced-technology effect.* Induced technological change reduces emissions among free riders (e.g. Di Maria and Van der Werf 2008).
- *Technology-spillover effect.* The emission constraint inside the "abatement coalition" generates improvements in abatement technology. These improvements spill over to free riders, which then decrease their emissions (Golombek and Hoel 2004; Gerlach and Kuik 2007).

Proposition 1 provides an alternative explanation of the strategic complementarity of emission policy as follows: If the rest of the world decreases its emissions m_{-j}, then, given preferences (2), the marginal disutility of total emissions in country j, $-\partial(C_j M^{-\delta_j})/\partial m_{-j}$, increases,

$$-\frac{\partial^2(C_j M^{-\delta_j})}{\partial m_{-j}^2} = -\frac{\partial^2(C_j M^{-\delta_j})}{\partial M^2} = -(\delta_j+1)\delta_j M^{-\delta_j-2}C_j.$$

This compels free rider $j \in (n, N]$ to reduce its emissions m_j. Because labor and emissions are complementary in production, labor input in production, l_j, falls. This decreases the wage, promoting labor-intensive R&D. A higher level of *R&D* speeds up economic growth.

3.3 Total emissions

Noting (1) and (10), total emissions $M = M^N$ are determined by

$$M = \int_0^n m_k dk + \int_n^N m_k(M) dk.$$

Noting (10), this equation defines the function

$$M = \mathcal{M}\left(\int_0^n m_k dk\right) \quad \text{with} \quad 1 < \mathcal{M}' = \frac{1}{1-\int_n^N m_k'(M)dk}$$
$$< \frac{1}{1-\frac{1}{M}\int_M^n m_k dk} = \frac{M}{M-\int_M^n m_k dk} = \frac{M}{\int_0^n m_k dk}. \tag{11}$$

Thus, emission policy in the coalition, $\int_0^n m_k dk$, is amplified by the multiplier $\mathcal{M}' > 1$ due to the response of the free riders.

4 Grandfathering

Grandfathering means that emission permits have a base that is determined by the history, but updated over time. In the quality-ladders model of this document, grandfathering can be specified as follows. The international agency sets the emission permits for country j, m_j, in fixed proportion $\varepsilon \in [0, 1]$ to the emissions of that country under previous technology, $\widehat{m}_j$:[2]

$$m_j = \varepsilon \widehat{m}_j \text{ for } j \in [0, n] \text{ and } \varepsilon \in [0, 1]. \tag{12}$$

[2]That is, if the current number of technology is given by τ_j, then the allocation base $\widehat{m}_j$ is calculated by emissions under previous technology $\tau_j - 1$ (cf. Subsection 2.3).

When the international agency tightens emission policy by decreasing ε, the rule (12) determines the emissions of the member countries, m_j for $j \in [0, n]$.

The international agency of the abatement coalition $[0, n]$ sets non-traded emission permits on its members $j \in [0, n]$, but it has no control over free riders $j \in (n, N]$. The coalition members $j \in [0, n]$ lobby the international agency over these permits. I assume that the members of the coalition share the same preferences and technology, for simplicity:[3]

$$\delta_j = \delta \text{ and } f^j(l_j, m_j) = f(l_j, m_j) \text{ for } j \in [0, n]. \tag{13}$$

Following Grossman and Helpman (1994), it is assumed that the international agency has its own interests and collects political contributions. Country $j \in [0, n]$ pays its contributions R_j in money terms to the international agency which decides on a specific emission permit m_j for this.

Let the set of emission permits be defined by $m_{[0,n]} \doteq \{m_k |\ k \in [0, n]\}$, and the set of political contributions by $R_{[0,n]} \doteq \{R_k |\ k \in [0, n]\}$. The order of the common agency game is then the following. First, the member countries $j \in [0, n]$ set their political contributions $R_{[0,n]}$ conditional on the international agency's prospective policy ε. Second, the international agency sets the permits ε and collects the contributions. Third, the countries maximize their utilities. This game is solved in reverse order: Subsection 4.1 considers countries and 4.2 the political equilibrium.

4.1 Optimal program

Country $j \in [0, n]$ pays political contributions R_j to the international agency. It is assumed, for simplicity, that the international agency consists of civil servants who inhabit countries $j \in [0, n]$ evenly. This implies that each country j gets an equal share $\frac{1}{n} \int_0^n R_k dk$ of total contributions. Thus, the net revenue of country $j \in [0, n]$ from political contributions is given by

[3] If the members were heterogeneous, then there is no unique solution for the menu auction models in Subsections 4.2 and 5.2.

$\frac{1}{n}\int_0^n R_k dk - R_j$ in money terms and $\big(\frac{1}{n}\int_0^n R_k dk - R_j\big)/P$ in real terms, where P is the price of the consumption good. Noting the choice of the numeraire, (3), and the production function (5), consumption in country j is then

$$C_j = Y_j + \frac{1}{P}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right) = a^{\gamma_j} f^j(l_j, m_j) + M^\delta\left(\frac{1}{n}\int_0^n R_k dk - R_j\right), \tag{14}$$

where Y_j is real income from production and $\big(\frac{1}{n}\int_0^n R_k dk - R_j\big)/P$ real net revenue from political contributions in country j.

Because total emission permits M and political contributions $R_{[0,n]}$ are not random variables, noting (13) and (14), the expected utility of country $j \in [0,n]$ starting at time T, (2), becomes

$$\begin{aligned}
\Upsilon^j &= E\int_T^\infty \left[a^{\gamma_j} f^j(l_j, m_j)M^{-\delta} + \frac{1}{n}\int_0^n R_k dk - R_j\right] e^{-\rho(\theta - T)} d\theta \\
&= E\int_T^\infty a^{\gamma_j} f^j(l_j, m_j)M^{-\delta} e^{-\rho(\theta - T)} d\theta + \left(\frac{1}{n}\int_0^n R_k dk - R_j\right)\int_T^\infty e^{-\rho(\theta-T)} d\theta \\
&= M^{-\delta} E\int_T^\infty a^{\gamma_j} f^j(l_j, m_j) e^{-\rho(\theta - T)} d\theta + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right).
\end{aligned} \tag{15}$$

Country $j \in [0,n]$ maximizes its expected utility (15) by its labor devoted to production, l_j, subject to Poisson technological change (7), given the emission permits $m_{[0,n]}$ and the political contributions $R_{[0,n]}$. The solution is this optimal program is given by (cf. Appendix B)

$$\begin{aligned}
&\Upsilon^j(m_{[0,n]}, R_{[0,n]}, M) \\
&= \frac{a^{\gamma_j(T)} f(l_j^*, m_j)}{\rho + (1-a)\lambda(1 - l_j^*)}\mathcal{M}\left(\int_0^n m_k dk\right)^{-\delta} + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right),
\end{aligned} \tag{16}$$

where $\gamma_j(T)$ is the serial number of technology at the initial time T and l_j^* is the optimal labor input for which

$$\frac{(a-1)\lambda l_j^*}{\rho + (1-a)\lambda(1 - l_j^*)} = 1 - \xi\left(\frac{l_j^*}{m_j}\right) \tag{17}$$

holds true. Noting (6), the partial derivatives of the function (16) are

$$\begin{aligned}\frac{\partial\Upsilon^j}{\partial m_j} &= \frac{a^{\gamma_j(T)} f(l_j^*, m_j) M^{-\delta}}{\rho + (1-a)\lambda(1-l_j^*)}\left[\frac{f_m(l_j, m_j)}{f(l_j, m_j)} - \frac{\delta}{M}\mathcal{M}'\right] \\ &= \frac{a^{\gamma_j(T)} f(l_j^*, m_j) M^{-\delta}}{\rho + (1-a)\lambda(1-l_j^*)}\left[\frac{1}{m_j}\xi\left(\frac{l_j}{m_j}\right) - \frac{\delta}{M}\mathcal{M}'\right], \\ \frac{\partial\Upsilon^j}{\partial m_k} &= -\frac{\delta\Gamma^j}{M^{\delta+1}}\mathcal{M}' \text{ for } k \in [0,n]\setminus\{j\}, \quad \frac{\partial\Upsilon^j}{\partial R_j} = \left(\frac{1}{n} - 1\right)\frac{1}{\rho}. \end{aligned} \tag{18}$$

4.2 The political equilibrium

Because each country $j \in [0,n]$ affects the international agency by its contributions R_j, its contribution schedule depends on the agency's policy ε:

$$R_j(\varepsilon), \;\; j \in [0,n], \quad R_{[0,n]}(\varepsilon) \doteq \{R_k(\varepsilon) | \;\, k \in [0,n]\}. \tag{19}$$

The international agency maximizes present value the expected flow of the real political contributions R_j from all countries $j \in [0,n]$:

$$G\big(R_{[0,n]}\big) \doteq E\int_T^\infty \left(\int_0^n R_j dj\right) e^{-\theta(\theta-T)} d\theta = \frac{1}{\rho}\int_0^n R_j dj. \tag{20}$$

Each country $j \in [0,n]$ maximizes its expected utility (16).

According to Dixit at al. (1997), a subgame perfect Nash equilibrium for this game is a set of contribution schedules $R_j(\varepsilon)$ and a policy ε such that the following conditions $(i) - (iv)$ hold:

(i) Contributions R_j are non-negative but no more than the contributor's income, $\Upsilon_j \geq 0$.

(ii) The policy ε maximizes the international agency's welfare (20) taking the contribution schedules $R_j(\varepsilon)$ as given,

$$\varepsilon \in \arg\max_\varepsilon G\big(R_{[0,n]}(\varepsilon)\big) = \arg\max_\varepsilon \int_0^n R_j(\varepsilon) dj; \tag{21}$$

(iii) Country j cannot have a feasible strategy $R_j(\varepsilon)$ that yields it a higher level of utility than in equilibrium, given the international agency's anticipated decision rule,

$$\varepsilon = \arg\max_{\varepsilon} \Upsilon^j\big(m_{[0,n]}, R_{[0,n]\setminus j}, R_j(\varepsilon)\big) \text{ with } m_j = \varepsilon \widehat{m}_j \text{ for } j \in [0,n]. \tag{22}$$

(iv) Country j provides the international agency at least with the level of utility than in the case it offers nothing ($R_j = 0$), and the agency responds optimally given the other countries contribution functions,

$$G\big(R_{[0,n]}(\varepsilon)\big) \geq \max_{\varepsilon} G\big(R_{[0,n]}(\varepsilon)\big)\Big|_{R_j=0}.$$

Noting (12) and (18), the condition (22) is equivalent to

$$0 = \frac{\partial \Upsilon^j}{\partial R_j}\frac{dR_j}{d\varepsilon} + \int_0^n \frac{\partial \Upsilon^j}{\partial m_k}\frac{\partial m_k}{\partial \varepsilon} dk = \left(\frac{1}{n} - 1\right)\frac{1}{\rho}\frac{dR_j}{d\varepsilon} + \int_0^n \frac{\partial \Upsilon^j}{\partial m_k}\widehat{m}_k dk$$

for $j \in [0,n]$ and

$$\frac{dR_j}{d\varepsilon} = \frac{\rho n}{1-n}\int_0^n \frac{\partial \Upsilon^j}{\partial m_k}\widehat{m}_k dk = \frac{\rho n \Gamma^j M^{-\delta}}{1-n}\left[\xi\left(\frac{l_j}{m_j}\right)\frac{\widehat{m}_j}{m_j} - \int_0^n \delta \frac{(M^N)'}{M}\widehat{m}_k dk\right]$$

for $j \in [0,n]$. Given these equations, one obtains

$$\int_0^n \frac{dR_j}{d\varepsilon} dj = \frac{\rho n M^{-\delta}}{1-n}\int_0^n \Gamma^j \left[\xi\left(\frac{l_j}{m_j}\right)\frac{\widehat{m}_j}{m_j} - \frac{\delta \mathcal{M}'}{\mathcal{M}}\int_0^n \widehat{m}_k dk\right] dj.$$

Noting this, the equilibrium condition (21) is equivalent to

$$\frac{\widehat{m}_j}{m_j}\xi\left(\frac{l_j}{m_j}\right) = \frac{\delta \mathcal{M}'}{\mathcal{M}}\int_0^n \widehat{m}_k dk. \tag{23}$$

Let us consider a stationary state where inputs (l_j, m_j) are independent of the number of technology τ_j for countries $j \in [0,n]$. Because the emissions of country j under the previous technology $\widehat{m}_j$ and under current technology m_j must be equal after subsequent changes in technology, it must be $\varepsilon = 0$ in the stationary state. The political equilibrium is specified by the equilibrium conditions (17) for all countries $j \in [0, n]$ plus that (23) for the international agency. In this system, there are unknown variables m_j and l_j for $j \in [0, n]$. This yields a stationary state with perfect symmetry:

$$l_j = l^N \text{ and } \widehat{m}_j = m_j = m^N \text{ for } j \in [0, n]. \tag{24}$$

Given this, (9) and (11), the equilibrium conditions (17) and (23) become

$$\xi\left(\frac{l^N}{m^N}\right) = \delta \frac{nm^N \mathcal{M}'(nm^N)}{\mathcal{M}(nm^N)}, \tag{25}$$

$$\frac{(a-1)\lambda l^N}{\rho + (1-a)\lambda(1-l^N)} = 1 - \xi\left(\frac{l^N}{m^N}\right). \tag{26}$$

4.3 Pareto optimum

If there were a benevolent international agency that would maximize the representative household's welfare in the coalition and make inter-countryal transfers for that purpose, it could entirely internalize the externality though GHG emissions and the outcome is a Pareto optimum. In that case, the coalition would behave as if there were a single jurisdiction, $n = 1$. Noting (24)-(26), this Pareto optimum (M^P, l^P, m^P) is given by

$$\xi\left(\frac{l^P}{m^P}\right) = \delta \frac{m^P \mathcal{M}'(m^P)}{\mathcal{M}(m^P)},$$

$$\frac{(a-1)\lambda l^P}{\rho + (1-a)\lambda(1-l^P)} = 1 - \xi\left(\frac{l^P}{m^M}\right), \tag{27}$$

where M^P total pollution in the world, l^P total labor input in production in the coalition and m^P total emissions in the coalition. Comparing the system (11)-(26) with the system (27) of three equations yields the following result:

Proposition 2 *With grandfathering, the coalition attains its Pareto optimum, i.e.* $M^P = M^N$, $l^P = nl^N$ *and* $m^P = nm^N$.

Proposition 2 can be explained as in Böringer and Lange (2005). The introduction of an international agency helps to internalize the negative externality through GHG emissions. With the uniform proportionality rule ε, all countries face the same marginal benefits from emissions via allocation in subsequent periods. Because the basis for allocation, $\widehat{m}_j$, can be updated over time, the international agency has a full control of resources. This holds true for both a benevolent and a self-interested agency. However, in contrast to Böringer and Lange (2005), the emission cap M^P is not exogenous but endogenously determined by the negotiation game between the member countries $j \in [0, n]$ and the international agency.

5 Emission permit trade

In this section, I extend the framework of the preceding section so that the countries in the abatement coalition $[0, n]$ can trade in emission permits among themselves. Thus, emission permits and actual emissions can differ.

I assume that the international agency has one policy instrument q_j for each country $j \in [0, n]$. With more instruments per country, the agency could deprive the countries $j \in [0, n]$ of their surpluses by two-part tariffs.[4] How should the instruments $q_{[0,n]} \doteq \{q_k | \ k \in [0, n]\}$ then be specified?

If the emission permits were given in the same units as emissions, emission permit trade would equalize the marginal products of emissions, $a^{\gamma_j} f_m^j(l_j, m_j)$ for all countries $j \in [0, n]$ in the coalition. In that case, a stationary state equilibrium (with constant inputs l_j and m_j) would be impossible, because the total factor productivity a^{γ_j} jumps at different times in different countries. Without a stationary state equilibrium, there would be no negotiation agreement between the countries and the international agency. To enable a stationary state equilibrium, it is assumed that the emission permits, q_j, are set for emissions m_j times the level of productivity, a^{γ_j} for country $j \in [0, n]$.

When country j has excess permits, $m_j a^{\gamma_j} < q_j$, it can sell the difference $q_j - m_j a^{\gamma_j}$ to the other members of the coalition at the price p. Correspondingly, when country j has excess emissions, $a^{\gamma_j} m_j > q_j$, it must buy

[4] Cf. Dixit el al. (1997).

the difference $m_j a^{\gamma_j} - q_j$ from the others at the price p. In equilibrium, the price p for emission permits adjusts so that the demand for emission permits, $\int_0^n m_j a^{\gamma_j} dj$, is equal to the supply of those, $\int_0^n q_k dk$:

$$\int_0^n m_j a^{\gamma_j} dj = \int_0^n q_k dk. \tag{28}$$

This modification changes the common agency game into the following. First, the countries set their political contributions $R_{[0,n]}$ conditional on the international agency's prospective policy $q_{[0,n]} \doteq \{q_k | \ k \in [0,n]\}$. Second, the international agency sets the permits $q_{[0,n]}$ and collect the contributions. Third, the price for permits p adjust to clear the market for emission permits. Fourth, the countries maximize their utilities. This game is solved in reverse order: Subsection 5.1 considers countries and 5.2 the political equilibrium.

5.1 Optimal program

With emission permit trade, consumption in country j, (29), changes into [cf. the numeraire (3)]

$$\begin{aligned} C_j &= Y_j + \frac{1}{P}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right) + \frac{p}{P}(q_j - m_j a^{\gamma_j}) \\ &= a^{\gamma_j} f^j(l_j, m_j) + M^\delta \left[\frac{1}{n}\int_0^n R_k dk - R_j + p(q_j - m_j a^{\gamma_j})\right], \end{aligned} \tag{29}$$

where Y_j is real income from production, $\left(\frac{1}{n}\int_0^n R_k dk - R_j\right)/P$ real net revenue from political contributions and $(p/P)\left(q_j - m_j a^{\gamma_j}\right)$ real net revenue from emission permit trade in country j. Because emission permits $q_{[0,n]}$ and political contributions $R_{[0,n]}$ are not random variables, noting (8) and (29), the expected utility of country $j \in [0,n]$ starting at time T, (15), becomes

$$\begin{aligned} \Delta^j &= E\int_T^\infty a^{\gamma_j}\left[\frac{f^j(l_j, m_j)}{M^\delta} - p m_j\right] e^{-\rho(\theta - T)} d\theta \\ &\quad + \left(\frac{1}{n}\int_0^n R_k dk - R_j + p q_j\right)\int_T^\infty e^{-\rho(\theta-T)} d\theta d\theta \\ &= E\int_T^\infty a^{\gamma_j}\left[\frac{f^j(l_j, m_j)}{(m_j + m_{-j})^\delta} - p m_j\right] e^{-\rho(\theta-T)} d\theta + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j + p q_j\right). \end{aligned} \tag{30}$$

Country j maximizes its expected utility (30) by emission and labor input (m_j, l_j) subject to Poisson technological change (7), given the permits $q_{[0,n]}$, the emission price p, emissions in the rest of the world, m_{-j}, and political contributions $R_{[0,n]}$. In Appendix C, it is shown that the solution of this optimal program is given by

$$\Delta^j(q_{[0,n]}, R_{[0,n]}) \doteq \frac{a^{\gamma_j(T)}}{\rho + (1-a)\lambda(1-l_j^*)}\left[\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^\delta} - p(m^T)m^T\right] + \frac{1}{\rho}\left[\frac{1}{n}\int_0^n R_k dk - R_j + p(m^T)q_j\right], \tag{31}$$

and the equilibrium conditions for l_j for any country $j \in [0, n]$ by

$$\frac{(a-1)\lambda l^T}{\rho + (1-a)\lambda(1-l^T)} = \frac{f(l^T, m^T)\mathcal{M}(nm^T)^{-\delta}}{f(l^T, m^T)\mathcal{M}(nm^T)^{-\delta} - p(m^T)m^T}\left[1 - \xi\left(\frac{l^T}{m^T}\right)\right], \tag{32}$$

where

$$p(m^T) \doteq \frac{f(l^T, m^T)}{\mathcal{M}(nm^T)^\delta m^T}\left[\xi\left(\frac{l^T}{m^T}\right) - \frac{\delta m^T}{\mathcal{M}(nm^T)}\right], \tag{33}$$

$$l_j = l^T \text{ and } m_j = m^T = \left(\int_0^n q_k dk\right)\Big/\int_0^n a^{\gamma_j} dj \text{ for } j \in [0, n]. \tag{34}$$

In Appendix C, I show furthermore that

$$\frac{\partial}{\partial q_k}\int_0^n \Delta^j(R_{[0,n]}, q_{[0,n]})dj = \frac{1}{\rho + (1-a)\lambda(1-l^T)}\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^\delta m^T} \times \left[\xi\left(\frac{l^T}{m^T}\right) - \delta\frac{nm^T\mathcal{M}'(nm^T)}{\mathcal{M}(nm^T)}\alpha(m^T) - \alpha(m^T)\lambda\right] \quad \text{for } k \in [0, n], \tag{35}$$

where

$$\alpha(m^T) \doteq [(a-1)\lambda(1-l^T)/\rho][p'(m^T)m^T + p(m^T)]\frac{\mathcal{M}(nm^T)^\delta m^T}{f(l^T, m^T)}. \tag{36}$$

5.2 The political equilibrium

The contribution schedules are functions of the international agency's policy variables (= the emission quotas) $q_{[0,n]}$:

$$R_j(q_{[0,n]}), \quad j \in [0, n]. \tag{37}$$

Each country $j \in [0,n]$ maximizes its expected utility (31) and the international agency maximizes its expected utility (20). A subgame perfect Nash equilibrium for this game is a set of contribution schedules $R_j(q_{[0,n]})$ and policy $q_{[0,n]}$ such that the conditions $(i)-(iv)$ in subsection 4.2 hold, with ε being replaced by $q_{[0,n]}$:

$$q_{[0,n]} = \arg\max_{q_{[0,n]}} G\big(R_{[0,n]}(q_{[0,n]})\big) = \arg\max_{q_{[0,n]}} \int_0^n R_j(q_{[0,n]})dj; \tag{38}$$

$$q_{[0,n]} = \arg\max_{q_{[0,n]}} \Delta^j\big(q_{[0,n]}, R_{[0,n]\setminus j}, R_j(q_{[0,n]})\big) \text{ for } j \in [0,n], \tag{39}$$

$$G\big(R_{[0,n]}(q_{[0,n]})\big) \geq \max_{q_{[0,n]}} G\big(R_{[0,n]}(q_{[0,n]})\big)\Big|_{R_j=0}.$$

Noting (31), the conditions (39) are equivalent to

$$0 = \frac{\partial \Delta^j}{\partial R_j}\frac{\partial R_j}{\partial q_k} + \frac{\partial \Delta^j}{\partial q_k} = -\frac{1}{\rho}\frac{\partial R_j}{\partial q_k} + \frac{\partial \Delta^j}{\partial q_k} \text{ for all } j \text{ and } k,$$

and

$$\frac{\partial R_j}{\partial q_k} = \rho\frac{\partial \Delta^j}{\partial q_k} \text{ for all } j \text{ and } k. \tag{40}$$

Noting (34), the first-order conditions of country j, (32), becomes

$$1 - \xi\Big(\frac{l^T}{m^T}\Big) = \frac{l^T f_l(l^T, m^T)}{f(l^T, m^T)} = \frac{(a-1)\lambda l^T}{\rho + (1-a)\lambda(1-l^T)}\left[1 - \frac{(M^T)^\delta m^T}{f(l^T, m^T)}p\right]. \tag{41}$$

Noting (35) and (40), the equilibrium conditions (38) are equivalent to

$$\frac{\partial}{\partial q_k}\int_0^n R_j dj = \rho\frac{\partial}{\partial q_k}\int_0^n \Delta^j dj = 0.$$

From this and (35) it follows that

$$\xi\Big(\frac{l^T}{m^T}\Big) = \delta\frac{nm^T \mathcal{M}'(nm^T)}{\mathcal{M}(nm^T)} + \alpha(m^T)\lambda. \tag{42}$$

5.3 The role of technological change

With $\lambda \to 0$, the equations (25) and (42) are the same, but the equations in (26) and (41) must be ignored, because there is no R&D [cf. (7)]. Thus, non-traded and traded permits lead to the same outcome. With $\lambda > 0$, the outcomes differ and, noting Proposition 2, a switch from non-traded to traded permits is a Pareto worsening. These results can be rephrased as:

Proposition 3 *If there were no technological change, $\lambda \to 0$, then emission permit trade would not make any difference, $l^N = l^T$, $m^N = m^T$ and $\xi^N = \xi^T$. With technological change $\lambda > 0$, the international agreement with emission permit trade is Pareto worsening.*

Proposition 3 can explained as follows. To enable a stationary state equilibrium, I assume that the emission permits for country j, q_j, are set for emissions m_j times the level of productivity in that country, a^{γ_j}. This means that country j discounts emissions costs pm_j according to the effective rate of return, $\rho + (1-a)\lambda(1-l_j)$, but the revenue from emission permits, pq_j, according to the rate of return, ρ [cf. (31)]. Consequently, at the level of the whole coalition, the value of the expenditure flow of emission costs outweighs that of the revenue flow from emission permits: noting (28), one obtains

$$\int_0^n \frac{a^{\gamma_j(T)} pm_j}{\rho + (1-a)\lambda(1-l_j)} dj - \int_0^n \frac{pq_j}{\rho} dj$$

$$= \left[\frac{1}{\rho + (1-a)\lambda(1-l^T)} - \frac{1}{\rho}\right] \int_0^n pq_j dj = \frac{\overbrace{(a-1)(1-l^T)}^{+}}{\underbrace{[\rho + (1-a)\lambda(1-l^T)]\rho}_{+}} \lambda > 0.$$

Without technological change, $\lambda \to 0$, the effective rate of return equals the rate of return, ρ, and emission permit trade makes no difference. If emission permits are distributed evenly, $q_j = q$, then, with technological change $\lambda > 0$, all countries will suffer, and if unevenly, then at least some of the countries will suffer from the introduction of emission trade.

6 Conclusions

This document examines the design of emission policy among a large number of countries which produce the same good, so that there is no terms-of-trade effect. Production anywhere in the world incurs GHG emissions that decrease welfare everywhere. Labor and emissions are complementary in production. Some countries can form an "abatement coalition", authorizing an international agency to grant them non-traded or traded GHG permits. This agency is self-interested, subject to lobbying, and has no budget of its own. The countries improve their productivity through research and development (R&D). This creates a link between emissions and economic growth, which affects the optimal design of emission policy.

Strategic complementarity in emission policy has been explained in the literature as follows: An increase in the free riders' real income due to better terms of trade decreases emissions (e.g. Copeland and Taylor 2005). Induced technological change leads to a reduction emissions among free riders as well (e.g. Di Maria and Van der Werf 2008). Improvements in abatement technology generated by the emission constraint spill over to free riders, which decrease their emissions (Golombek and Hoel 2004; Gerlach and Kuik 2007). As an alternative explanation, I present a *complementary effect* as follows: If the rest of the world cuts their emissions down, then the marginal disutility of total emissions increases, encouraging the countries to reduce their emissions. Because labor and emissions are complementary in production, labor input in production falls. This decreases the wage and promotes labor-intensive R&D. With a higher level of $R\&D$, economic growth is faster.

The introduction of an international agency into the "abatement coalition" helps to internalize the negative externality through GHG emissions. With grandfathering, all countries face the same marginal benefits from emissions via allocation in subsequent periods. Because the basis for allocation can be updated over time, the international agency has a full control of resources and the outcome is Pareto optimal. This holds true for both a benevolent and a self-interested international agency.

With emission permit trade, the situation is more complicated. First, the international agency should not have more policy instruments than one per country. Otherwise, it will reap all surpluses from the countries in a negotiation game. This means that country-specific emission permit is the feasible set of instruments for the the international agency. Second, in order to have an agreement in a negotiation game, the system must have a stationary state equilibrium. This is possible only, if emission permits are set in proportion to the local productivity in each country. Consequently, at the level of the whole coalition, the value of the expenditure flow of emission costs outweighs that of the revenue flow from emission permits. Thus, at least some countries will suffer from the introduction of emission permit trade and a stationary state equilibrium with emission permit trade is not sustainable.

Appendix

A Functions (10)

The value of the optimal program is given by

$$\Omega^j(\gamma_j, m_{-j}, T) \doteq \max_{(m_j, l_j)\text{ s.t. } (7)} E \int_T^\infty \frac{a^{\gamma_j} f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j}} e^{-\rho(t-T)} dt. \tag{43}$$

I denote the value of the optimal program of country j with current technology γ_j by $\Omega^j = \Omega^j(\gamma_j, m_{-j}, T)$ and that with future technology $\gamma_j + 1$ by $\widetilde{\Omega}^j = \Omega^j(\gamma_j + 1, m_{-j}, T)$. The Bellman equation corresponding to the optimal program (43) is then

$$\rho\Omega^j = \max_{m_j, l_j} \Phi^j(m_j, l_j, \gamma_j, m_{-j}, T), \quad \text{where} \tag{44}$$

$$\Phi^j(m_j, l_j, \gamma_j, m_{-j}, T) = \frac{a^{\gamma_j} f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j}} + \lambda(1 - l_j)\big[\widetilde{\Omega}^j - \Omega^j\big]. \tag{45}$$

Noting (6), this leads to the first-order conditions

$$\begin{aligned}
\frac{\partial \Phi^j}{\partial m_j} &= a^{\gamma_j}\left[\frac{f_m^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j}} - \frac{\delta_j f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j + 1}}\right] \\
&= a^{\gamma_j}\left[\frac{f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j} m_j}\xi_j\left(\frac{l_j}{m_j}\right) - \frac{\delta_j f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j + 1}}\right]
\end{aligned}$$

$$= a^{\gamma_j} \frac{f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j} m_j} \left[\xi_j \left(\frac{l_j}{m_j} \right) - \frac{\delta_j m_j}{m_j + m_{-j}} \right] = 0, \tag{46}$$

$$\frac{\partial \Phi^j}{\partial l_j} = \frac{a^{\gamma_j} f_l^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j}} - \lambda \big[\widetilde{\Omega}^j - \Omega^j \big]$$

$$= \frac{a^{\gamma_j} f^j(l_j, m_j)}{(m_j + m_{-j})^{\delta_j} l_j} \left[1 - \xi_j \left(\frac{l_j}{m_j} \right) \right] - \lambda \big[\widetilde{\Omega}^j - \Omega^j \big] = 0. \tag{47}$$

To solve the dynamic program (43), I try the solution that the value of the program, Ω^j, is in fixed proportion $\varphi_j > 0$ to instantaneous utility:

$$\Omega^j(\gamma_j, m_{-j}, T) = \varphi_j a^{\gamma_j} \frac{f^j(l_j^*, m_j^*)}{(m_j^* + m_{-j})^{\delta_j}}, \tag{48}$$

where (l_j^*, m_j^*) are the optimal values of (l_j, m_j). This implies

$$\widetilde{\Omega}^j / \Omega^j = a. \tag{49}$$

Inserting (48) and (49) into the Bellman equation (44) and (45) yields

$$1/\varphi_j = \rho + (1 - a)\lambda(1 - l_j) > 0. \tag{50}$$

Inserting (8), (48), (49) and (50) into the conditions (46) and (47) yields

$$\xi_j \left(\frac{l_j}{m_j} \right) = \frac{\delta_j m_j}{m_j + m_{-j}} = \frac{\delta_j m_j}{M} \in (0, 1), \tag{51}$$

$$0 = \varphi_j \frac{l_j}{\Omega^j} \frac{\partial \Phi^j}{\partial l_j} = \underbrace{\frac{a^{\gamma_j} f^j(l_j, m_j) \varphi_j}{(m_j + m_{-j})^{\delta_j} \Omega^j}}_{=1} \left[1 - \xi_j \left(\frac{l_j}{m_j} \right) \right] - \lambda \varphi_j l_j \Bigg[\underbrace{\frac{\widetilde{\Omega}^j}{\Omega^j}}_{=a} - 1 \Bigg]$$

$$= 1 - \xi_j \left(\frac{l_j}{m_j} \right) - \frac{(a - 1)\lambda l_j}{\rho + (1 - a)\lambda(1 - l_j)}. \tag{52}$$

The equations (51) and (52) can be transformed into

$$\log \xi(l_j/m_j) + \log M - \log m_j = \text{constants},$$
$$\log l_j - \big[\xi_j (l_j/m_j)^{-1} - 1 \big] = \text{constants}.$$

Differentiating this system totally and noting (6), one obtains

$$\frac{dm_j}{dM} = \frac{1}{M} \int_n^N m_j \left[\frac{1}{l_j} + \frac{\xi_j'/\xi_j}{(1 - \xi_j) m_j} \right] \Bigg[\underbrace{\frac{\xi_j'}{m_j \xi_j}}_{+} + \frac{1}{l_j} + \frac{\xi_j'/\xi_j}{(1 - \xi_j) m_j} \Bigg]^{-1} dj$$

$$< \frac{1}{M}\int_n^N m_j dj < 1,$$

$$\frac{\partial l_j}{\partial M} = \frac{m_j}{M}\underbrace{\frac{(\xi_j'/\xi_j)l_j}{(1-\xi_j)(m_j)^2}}_{+}\Bigg[\underbrace{\frac{\xi_j'}{m_j\xi_j}}_{+}+\frac{1}{l_j}+\underbrace{\frac{\xi_j'/\xi_j}{(1-\delta_j\xi_j)m_j}}_{+}\Bigg]^{-1} > 0,$$

From this and (4) it follows that $dz_j/dM = -dl_j/dM < 0$.

B Function (16) and condition (17)

Country $j \in [0, n]$ maximizes (15) by l_j subject to (7), given $m_{[0,n]}$ and $R_{[0,n]}$. It is equivalent to maximize

$$E\int_T^\infty a^{\gamma_j} f(l_j, m_j)e^{-\rho(t-T)}dt$$

by l_j subject to (7), given m_j and M. The value of this maximization is

$$\Gamma^j(\gamma_j, m_j, T) = \max_{l_j \text{ s.t. } (7)} E\int_T^\infty a^{\gamma_j} f(l_j, m_j)e^{-\rho(t-T)}dt. \tag{53}$$

I denote $\Gamma^j = \Gamma^j(\gamma_j, m_j, T)$ and $\widetilde{\Gamma}^j = \Gamma^j(\gamma_j + 1, m_j, T)$. The Bellman equation corresponding to the optimal program (53) is

$$\rho\Gamma^j = \max_{l_j} \Psi^j(l_j, \gamma_j, m_j, T), \quad \text{where} \tag{54}$$

$$\Psi^j(l_j, \gamma_j, m_j, T) = a^{\gamma_j} f(l_j, m_j) + \lambda(1 - l_j)\big[\widetilde{\Gamma}^j - \Gamma^j\big]. \tag{55}$$

Noting (6), this leads to the first-order condition

$$\frac{\partial \Psi^j}{\partial l_j} = a^{\gamma_j} f_l(l_j, m_j) - \lambda\big[\widetilde{\Gamma}^j - \Gamma^j\big] = a^{\gamma_j}\frac{f(l_j, m_j)}{l_j}\left[1 - \xi\left(\frac{l_j}{m_j}\right)\right] - \lambda\big[\widetilde{\Gamma}^j - \Gamma^j\big]$$
$$= 0. \tag{56}$$

To solve the dynamic program (53), I try the solution that the value of the program, Γ^j, is in fixed proportion $\vartheta_j > 0$ to instantaneous utility:

$$\Gamma^j(\gamma_j, m_j, T) = \vartheta_j a^{\gamma_j} f(l_j^*, m_j), \tag{57}$$

where l_j^* is the optimal value of the control variable l_j. This implies

$$(\widetilde{\Gamma}^j - \Gamma^j)/\Gamma^j = a - 1. \tag{58}$$

Inserting (57) and (58) into the Bellman equation (54) and (55) yields

$$1/\vartheta_j = \rho + (1-a)\lambda(1-l_j^*) > 0. \tag{59}$$

Inserting (57), (58) and (59) into (56), one obtains (17):

$$\begin{aligned}0 = \vartheta_j \frac{l_j}{\Gamma^j}\frac{\partial \Psi^j}{\partial l_j} &= \underbrace{a^{\gamma_j} f(l_j, m_j)\frac{\vartheta_j}{\Gamma^j}}_{=1}\left[1 - \xi\left(\frac{l_j}{m_j}\right)\right] - \left(\underbrace{\frac{\widetilde{\Gamma}^j}{\Gamma_j}}_{=a} - 1\right)\lambda l_j \vartheta_j \\ &= 1 - \xi\left(\frac{l_j}{m_j}\right) - \frac{(a-1)\lambda l_j}{\rho + (1-a)\lambda(1-l_j^*)}.\end{aligned}$$

Noting (53), (57), (59) and (11), the expected utility of country j, (15), becomes (16):

$$\begin{aligned}\Upsilon^j(m_{[0,n]}, R_{[0,n]}, M) &= \Gamma^j(\gamma_j, m_j, T)M^{-\delta} + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right) \\ &= \vartheta_j a^{\gamma_j(T)} f(l_j^*, m_j)\mathcal{M}\left(\int_0^n m_k dk\right)^{-\delta} + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right) \\ &= \frac{a^{\gamma_j(T)} f(l_j^*, m_j)}{\rho + (1-a)\lambda(1-l_j^*)}\mathcal{M}\left(\int_0^n m_k dk\right)^{-\delta} + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j\right),\end{aligned}$$

where the optimal value l_j^* of the control variable l_j is taken as given.

C Function (32) and conditions (31) and (33)

Country j maximizes its expected utility (30) by emission and labor input (m_j, l_j) subject to Poisson technological change (7), given the permits $q_{[0,n]}$, the emission price p, emissions in the rest of the world, m_{-j}, and political contributions $R_{[0,n]}$. It is equivalent to maximize

$$\int_T^\infty a^{\gamma_j}\left[f(l_j, m_j)(m_j + m_{-j})^{-\delta} - p m_j\right] e^{-\rho(t-T)} dt$$

by (l_j, m_j) subject to (7), given r, $\{q_k\}$, p, m_{-j} and R_j. The value of the optimal program for country j can then be defined as follows:

$$\Gamma^j(\gamma_j, p, m_{-j}, T) \\ = \max_{(m_j, l_j) \text{ s.t. } (7)} E\int_T^\infty a^{\gamma_j}\big[f(l_j, m_j)(m_j + m_{-j})^{-\delta} - pm_j\big]e^{-\rho(t-T)}dt. \quad (60)$$

I denote $\Gamma^j = \Gamma^j(\gamma_j, p, m_{-j}, T)$ and $\widetilde{\Gamma}^j = \Gamma^j(\gamma_j + 1, p, m_{-j}, T)$. The Bellman equation corresponding to the optimal program (60) is

$$\rho\Gamma^j = \max_{l_j, m_j} \Psi^j(l_j, \gamma_j, p, m_{-j}, T), \quad \text{where} \quad (61)$$

$$\Psi^j(l_j, \gamma_j, p, m_{-j}, T) = a^{\gamma_j}\left[\frac{f(l_j, m_j)}{(m_j + m_{-j})^\delta} - pm_j\right] + \lambda(1 - l_j)\big[\widetilde{\Gamma}^j - \Gamma^j\big]. \quad (62)$$

This leads to the first-order conditions (63) and (64):

$$\frac{\partial\Psi^j}{\partial m_j} = a^{\gamma_j}\left[\frac{f_m(l_j, m_j)}{(m_j + m_{-j})^\delta} - \frac{\delta f(l_j, m_j)}{(m_j + m_{-j})^{\delta+1}} - p\right] = 0, \quad (63)$$

$$\frac{\partial\Psi^j}{\partial l_j} = \frac{a^{\gamma_j} f_l(l_j, m_j)}{(m_j + m_{-j})^\delta} - \lambda\big[\widetilde{\Gamma}^j - \Gamma^j\big] = 0. \quad (64)$$

To solve the dynamic program (60), I try the solution that the value of the program, Γ^j, is in fixed proportion $\varpi_j > 0$ to instantaneous utility:

$$\Gamma^j(\gamma_j, p, m_{-j}, T) = \varpi_j a^{\gamma_j}\left[\frac{f(l_j^*, m_j^*)}{(m_j^* + m_{-j})^\delta} - pm_j^*\right], \quad (65)$$

where (l_j^*, m_j^*) are the optimal values of (l_j, m_j). This implies

$$(\widetilde{\Gamma}^j - \Gamma^j)/\Gamma^j = a - 1. \quad (66)$$

Inserting (65) and (66) into the Bellman equation (61) and (62) yields

$$1/\varpi_j = \rho + (1 - a)\lambda(1 - l_j^*) > 0. \quad (67)$$

Given (60), (65), (67), country j's utility (30) is defined as a function of political contributions $R_{[0,n]}$ and emission permits $q_{[0,n]}$:

$$\Delta^j = \Gamma^j(\gamma_j, p, m_{-j}, T) + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j + pq_j\right)$$

$$= \varpi_j a^{\gamma_j(T)}\left[\frac{f(l_j^*, m_j^*)}{(m_j^* + m_{-j})^\delta} - pm_j^*\right] + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j + p(m^T)q_j\right)$$
$$= \frac{a^{\gamma_j(T)}}{\rho + (1-a)\lambda(1-l_j^*)}\left[\frac{f(l_j^*, m_j^*)}{(m_j^* + m_{-j})^\delta} - pm_j^*\right] + \frac{1}{\rho}\left(\frac{1}{n}\int_0^n R_k dk - R_j + pq_j\right). \tag{68}$$

Noting (6), (65), (66) and (67), the first-order conditions (63) and (64) change into (69) and (70):

$$\begin{aligned} p &= \frac{f_m(l_j^*, m_j)}{(m_j + m_{-j})^\delta} - \frac{\delta f(l_j, m_j)}{(m_j + m_{-j})^{\delta+1}} \\ &= \frac{f(l_j, m_j)}{(m_j + m_{-j})^\delta m_j}\left[\frac{m_j f_m(l_j, m_j)}{f(l_j, m_j)} - \frac{\delta m_j}{m_j + m_{-j}}\right] \\ &= \frac{f(l_j, m_j)}{(m_j + m_{-j})^\delta m_j}\left[\xi\left(\frac{l_j}{m_j}\right) - \frac{\delta m_j}{m_j + m_{-j}}\right], \end{aligned} \tag{69}$$

$$\begin{aligned} 0 = \varpi_j \frac{l_j}{\Gamma^j}\frac{\partial \Psi^j}{\partial l_j} &= \frac{a^{\gamma_j} f_l(l_j, m_j) l_j \varpi_j}{(m_j + m_{-j})^\delta \Gamma^j} - \lambda l_j \varpi_j \left(\underbrace{\frac{\widetilde{\Gamma}^j}{\Gamma^j}}_{=a} - 1\right) \\ &= \frac{l_j f_l(l_j, m_j)(m_j + m_{-j})^{-\delta}}{f(l_j, m_j)(m_j + m_{-j})^{-\delta} - pm_j} - \frac{(a-1)\lambda l_j}{\rho + (1-a)\lambda(1-l_j)} \\ &= \frac{f(l_j, m_j)(m_j + m_{-j})^{-\delta}}{f(l_j, m_j)(m_j + m_{-j})^{-\delta} - pm_j}\left[1 - \xi\left(\frac{l_j}{m_j}\right)\right] - \frac{(a-1)\lambda l_j}{\rho + (1-a)\lambda(1-l_j)}. \end{aligned} \tag{70}$$

In the system of the equilibrium conditions $m_{-j} = M - m_j$ [cf. (8)], (69) and (70) for all $j \in [0, n]$, there are the unknown variables (l_j, m_j) for $j \in [0, n]$ and the known variables M and p. Because in this system there is perfect symmetry throughout $j \in [0, n]$, one obtains

$$l_j^* = l_j = l^T \text{ and } m_j^* = m_j = m^T \text{ for } j \in [0, n]. \tag{71}$$

Plugging (71) into (8), (11) and (28) yields

$$\begin{aligned} &m^T = \left(\int_0^n q_k dk\right)\Big/\int_0^n a^{\gamma_j} dj, \quad M = \mathcal{M}(nm^T), \\ &m_{-j}(m^T) \doteq \mathcal{M}(nm^T) - m^T. \end{aligned} \tag{72}$$

Inserting (71) and (72) into (69), one can define

$$p(m^T) \doteq \frac{f(l^T, m^T)}{\mathcal{M}(nm^T)^{\delta} m^T} \left[\xi\left(\frac{l^T}{m^T}\right) - \frac{\delta m^T}{\mathcal{M}(nm^T)} \right]. \tag{73}$$

Noting (71)-(73), one obtains that the expected utility of country j, (68), and the equilibrium condition (70) are for given $q_{[0,n]}$ determined as follows:

$$\begin{aligned} \Delta^j(q_{[0,n]}, R_{[0,n]}) \doteq{}& \frac{a^{\gamma_j}}{\rho + (1-a)\lambda(1-l_j^*)} \left[\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^{\delta}} - p(m^T)m^T \right] \\ &+ \frac{1}{\rho}\left[\frac{1}{n}\int_0^n R_k dk - R_j + p(m^T)q_j \right], \end{aligned} \tag{74}$$

$$\frac{(a-1)\lambda l^T}{\rho + (1-a)\lambda(1-l^T)} = \frac{f(l^T, m^T)\mathcal{M}(nm^T)^{-\delta}}{f(l^T, m^T)\mathcal{M}(nm^T)^{-\delta} - p(m^T)m^T} \left[1 - \xi\left(\frac{l^T}{m^T}\right) \right]. \tag{75}$$

The results (31), (33) and (32) are given by (74), (73) and (75).

Noting (73) and (34), the sum of the functions (31) is given by

$$\begin{aligned} &\int_0^n \Delta^j(R_{[0,n]}, q_{[0,n]}) dj \\ &= \int_0^n \frac{a^{\gamma_j}}{\rho + (1-a)\lambda(1-l_j^*)} \left[\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^{\delta}} - p(m^T)m^T \right] dj + \frac{p(m^T)}{\rho} \int_0^n q_j dj \\ &= \left\{ \frac{1}{\rho + (1-a)\lambda(1-l_j^*)} \left[\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^{\delta}} - p(m^T)m^T \right] + \frac{m^T p(m^T)}{\rho} \right\} \int_0^n a^{\gamma_j} dj. \end{aligned}$$

Noting and (6), (34) and $l_j^* = l^T$ for all $j \in [0, n]$, this leads to

$$\begin{aligned} &\frac{\partial}{\partial q_k} \int_0^n \Delta^j(R_{[0,n]}, q_{[0,n]}) dj \\ &= \frac{\partial}{\partial m^T} \left\{ \frac{1}{\rho + (1-a)\lambda(1-l_j^*)} \left[\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^{\delta}} - p(m^T)m^T \right] + \frac{m^T p(m^T)}{\rho} \right\} \\ &\qquad \underbrace{\left(\int_0^n a^{\gamma_j} dj \right) \frac{\partial m^T}{\partial q_j}}_{=1} \\ &= \frac{\partial}{\partial m^T} \left\{ \frac{1}{\rho + (1-a)\lambda(1-l_j^*)} \left[\frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^{\delta}} - p(m^T)m^T \right] + \frac{m^T p(m^T)}{\rho} \right\} \end{aligned}$$

$$
\begin{aligned}
&= \frac{1}{\rho + (1-a)\lambda(1-l_j^*)} \frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^\delta} \left[\frac{f_m(l_j^*, m^T)}{f(l_j^*, m^T)} - n\delta \frac{\mathcal{M}'(nm^T)}{\mathcal{M}(nm^T)} \right] \\
&\quad + \left[\frac{1}{\rho} - \frac{1}{\rho + (1-a)\lambda(1-l_j^*)} \right] [p'(m^T)m^T + p(m^T)] \\
&= \frac{1}{\rho + (1-a)\lambda(1-l_j^*)} \frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^\delta} \left[\frac{1}{m^T} \xi\left(\frac{l_j^*}{m^T} \right) - n\delta \frac{\mathcal{M}'(nm^T)}{\mathcal{M}(nm^T)} \right] \\
&\quad + \frac{(1-a)\lambda(1-l_j^*)/\rho}{\rho + (1-a)\lambda(1-l_j^*)} [p'(m^T)m^T + p(m^T)] \\
&= \frac{1}{\rho + (1-a)\lambda(1-l^T)} \left\{ \frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^\delta m^T} \left[\xi\left(\frac{l^T}{m^T} \right) - \delta \frac{nm^T \mathcal{M}'(nm^T)}{\mathcal{M}(nm^T)} \right] \right. \\
&\quad \left. + [(1-a)\lambda(1-l^T)/\rho][p'(m^T)m^T + p(m^T)] \right\} \\
&= \frac{1}{\rho + (1-a)\lambda(1-l^T)} \frac{f(l_j^*, m^T)}{\mathcal{M}(nm^T)^\delta m^T} \\
&\quad \times \left[\xi\left(\frac{l^T}{m^T} \right) - \delta \frac{nm^T \mathcal{M}'(nm^T)}{\mathcal{M}(nm^T)} - \alpha(m^T)\lambda \right] \quad \text{for } k \in [0, n],
\end{aligned}
$$

where $\alpha(m^T)$ is defined by (36).

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