100

■

The Burden Sharing of Pollution Abatement Costs in Multi-Regional Open Economics

Raouf Boucekkine and Marc Germain

January 2009

ENVIRONMENTAL
ECONOMICS & MANAGEMENT
MEMORANDUM

UCL
Université
catholique
de Louvain

Chair Lhoist Berghmans
in Environmental Economics
and Management

Center for Operations Research
and Econometrics (CORE)

The B.E. Journal of Macroeconomics

Topics

Volume 9, *Issue* 1 2009 *Article* 21

The Burden Sharing of Pollution Abatement Costs in Multi-Regional Open Economies

Raouf Boucekkine[*] Marc Germain[†]

[*]Université Catholique de Louvain, boucekkine@ires.ucl.ac.be

[†]Université Catholique de Louvain, marc.germain@uclouvain.be

Recommended Citation

Raouf Boucekkine and Marc Germain (2009) "The Burden Sharing of Pollution Abatement Costs in Multi-Regional Open Economies," *The B.E. Journal of Macroeconomics*: Vol. 9: Iss. 1 (Topics), Article 21.

Available at: http://www.bepress.com/bejm/vol9/iss1/art21

The Burden Sharing of Pollution Abatement Costs in Multi-Regional Open Economies*

Raouf Boucekkine and Marc Germain

Abstract

The burden sharing of pollution abatement costs raises the issue of how the costs are supported by entities (regions or industries) of a country that decides to reduce pollution, e.g., in the Kyoto Protocol context. This paper explores this issue in the framework of a dynamic endogenous growth 2 sectors - 2 regions - 2 inputs Heckscher-Ohlin model of a small open economy with an international tradable permits market. Given an "emission-based grand-fathering" sharing rule, capital accumulation is more negatively affected by the environmental policy in the energy intensive sector if energy and capital are complementary. But the picture could be different in terms of total sectoral revenue, depending on the evolution of prices. Finally, we show that the impact of environmental policy at the regional level depends crucially on the evolution of regional specialization patterns.

KEYWORDS: pollution permits, grand-fathering, sectoral spillovers, multi-regional economy, endogenous growth

---

*We are indebted to two anonymous referees and to the editor, Peter Ireland, for numerous suggestions which have decisively shaped this version. Raouf Boucekkine acknowledges the support of the French National Agency for Research (ANR) through an ACI contract on sustainable development and technological progress. The usual disclaimer applies.

1 Introduction

The burden sharing of pollution abatement costs raises the issue of how the costs are supported by entities (regions or industries) of a country that decides to reduce pollution, e.g. in the Kyoto Protocol context. In Belgium, the debate opposes the Flemish and Walloon regions. With respect to the other Belgian regions, Wallonia is characterized by an industry which is more energy consuming. From the point of view of Flanders, the burden should thus largely rely on Wallonia, where the abatement measures are supposed to be less expensive. On the contrary, this solution is considered to be too unfavorable by Wallonia.

Now it is important to emphasize that the fact that a country's activities are more energy consuming does not necessarily result from any inefficiency. It can result from the specialization of this country in the production of relatively energy intensive goods. The importance of accounting for different national circumstances (resulting a.o. from international specialization) when designing future climate mitigation commitments is mentioned in several articles of the United Nations Framework Convention on Climate Change. As stressed by den Elzen and Berk (2004,p.41), "A climate change regime that fails to take account of such circumstances may result in disproportional or abnormal burdens for some (groups of) countries. This would not just be unfair, but also politically unacceptable".

In a multi-regional multi-sectoral framework, the following properties are generally expected to occur in response to an environmental policy that increases the price of energy (through an energy tax or through the tradable permits price):

(A) the energy intensive sectors are more burdened than the other sectors;

(B) the regions specialized in energy intensive sectors are more burdened than the other regions.

Hereafter we will refer to these properties as Expected Results A and B (ERA and ERB respectively). These results are common wisdom. However, they are not so obvious as it could be thought at first sight, and in any case, they do depend on how the burden is measured, e.g. whether one takes into account or not the tax revenues or the tradable permit endowments associated to the control of pollution. The impact of an emission reduction policy can indeed be modulated by bringing into play such regional transfers and allocations.[1] Furthermore, even if permit endowments or tax revenues are ignored, we will show that the conclusions w.r.t. ERA depend on whether the burden is measured in terms of capital accumulation or in terms of sectoral revenues (defined as output less intermediate consumption).

On the other hand, even if ERB is verified at a given date, this does not mean that the more affected region in the short term will remain so in the long run. This is because the specialization patterns are likely to evolve through time, implying that the regional impact of a long term environmental policy (like climate policies) is also likely to get modified after a while.

In this paper, we shall consider a dynamic model allowing for specialization reversal[2]. One way to get such a property is to incorporate time-dependent spillovers across economic sectors and regions. There is an extensive literature about spillovers both at a regional or international level. In particular, the empirical assessment of such spillovers have been at the heart of a quite abundant empirical literature. An early contribution to the topic is due to Coe and Helpman (1995) who assessed the economic growth impact of R&D expenditures in OECD (Organisation for Economic Cooperation and Development) countries. They found that such expenditures are beneficial not only for the performing countries but also for the trade partners. There are also plenty of empirical contributions addressing the issue of spillovers' extent at a regional level (see among others Van Stel and Nieuwenhuijsen, 2004).

One of the crucial issues turns out to be whether intra-sectoral or inter-sectoral spillovers are more important for economic growth. As to this precise point, the evidence is mixed. A recent study by Malerba, Mancusi and Montobbio (2004) tends however to put forward intra-sectoral spillovers. Using a panel data on R&D expenditures and patent citations in 135 sectors in France, Italy, Japan, United-Kingdom and the US over the period 1981-1995, they show that the effect of intra-sectoral spillovers is 70% higher than the effect of national inter-sectoral spillovers. We shall incorporate intra-sectoral spillovers in our model. As we shall see in Section 2, considering at the same time inter and intra-sectoral spillovers in our model would induce the same long-run

---

[1] These transfers can follow numerous rules (see Rose et al, 1998). Two rules were extensively debated in Belgium: following the emission reduction policy, (i) the first rule assumes that the regional endowments of permits decrease by the same percentage, and (ii) the second rule assumes that the endowment of a region decreases proportionally to the decrease of its emissions induced by an optimal reduction policy at the level of the country. In both cases, Germain et al. (2006) show that Wallonia suffers more from the emission reduction policy than Flanders.

[2] Contrary to the analysis of Germain et al. (2006) which presents the drawback to be static, and thus cannot take account of specialization reversal.

capital accumulation in ALL sectors and in ALL regions, which sounds an undesirable outcome as it implies that the sectoral composition of the economy is irrelevant in the long-run.[3]

The aim of this paper is to study the impact of long term environmental policies in the framework of a dynamic 2 sectors - 2 regions - 2 inputs (capital and energy) Heckscher-Ohlin model of a small open multi-regional economy with an international tradable permits market.[4] The main features of the model are the following. Sector 1 produces capital goods while sector 2 produces consumer goods. Energy is imported and emissions are proportional to energy use. The technologies of both sectors are constant elasticity of substitution (CES) production functions. Sector 1 is more energy intensive than sector 2. The sectoral technologies are the same in both regions. Because the country is treated as a small open economy, prices are determined by the rest of the world and are thus exogenous. One of the two regions is specialized in the production of the energy intensive good. Growth in endogenous: returns to scale are decreasing at the level of the firm, but because of the (intra-sectoral) technological spillovers, returns to scale are constant at the sectoral level. Spillovers are modeled in the spirit of the Arrowian learning-by-investing mechanism, resuscitated by Romer (1986). Introducing R&D expenditures would have complicated unnecessarily the model given our main objectives. Rather we consider the shortcut of learning-by-investing to get a tractable yet far from trivial inter-sectoral inter-regional growth model.[5]

The country is assumed to face an exogenously given intertemporal objective in terms of pollution reduction inherited from international obligations (e.g. the Kyoto Protocol and its successive steps)[6]. To this objective corresponds a sequence of permit endowments. Given that a country has considerable freedom in the choice of the specific allocation mechanism of permits across its industries (Böhringer and Lange, 2005), the government of the country shares the permits between polluting firms following a certain rule. These

---

[3] Recent studies on two-sector growth models tend rather to emphasize that investment-specific technological progress is likely to generate a persistent productivity gap between the capital good and consumption good sectors, see Greenwood, Hercowitz and Krusell (1997).

[4] In this respect, our paper is linked to the literature on trade and environment. Contributions to this strand of literature are a.o. Antweiler et al. (2001), Copeland and Taylor (2003) and Batabyal and Beladi (2001). More specifically, articles that develop (as in the present paper) a dynamic model of a small open economy are those of Copeland and Taylor (1997) and Lee and Batabyal (2002). See also Ishikawa and Kiyono (2006).

[5] Boucekkine, del Rio and Licandro (2003) have already studied two-sector models with learning-by-investing in each sector. However, they consider a non-regional closed-economy.

[6] Our approach is thus positive and not normative. We are not concerned by the optimality or sub-optimality of the country's objective.

permits are tradable on an international market at a given exogenous price.

Following Böhringer and Lange (2005) and Rehdanz and Tol (2004), we will focus on a dynamic emission-based grand-fathering rule (also called rolling grand-fathering), where the permit endowment of a firm is a function of its past emissions. This specification can be justified by the fact that "in most existing emissions trading systems (e.g. the SO2 trading in the USA), emission allowances are grand-fathered according to historical firm data on emissions or fuel use. However permit endowments that only rely on historical data previous to the reduction objective (i.e. without updating) cannot account for changes in market conditions, e.g. for changing firm size or for new entrants. Therefore, allocation plans that update the basis for allocation from period to period may be politically more attractive." (Böhringer and Lange, 2005). This feature can be internalized by firms or not.

The paper is organized as follows. Section 2 describes the model and characterizes optimal capital accumulation per sector and region. Section 3 is devoted to study the impact of environmental policy in the framework of an international permits market. First, we accurately describe the main assumptions underlying the baseline (no policy) scenario. Second the impact of the environmental policy is evaluated, first at the sectoral level, then at the regional level. Third, we summarize our findings, and more importantly, we confront them to ERA and ERB. Section 4 concludes.

2 The model

We model a 2 regions - 2 sectors - 2 inputs small open multi-regional economy where :
- the 2 regions are indexed by i ($i = v, w$),
- the 2 sectors (or 2 goods) are indexed by j ($j = a, b$),
- the 2 inputs are capital (k) and fossil energy (e).

Capital is understood in a broad sense, i.e. as a bundle of inputs like physical and human capital, infrastructures, non-fossil energy,... Given that we consider a small open economy, agents are price-takers, and prices are determined by the rest of the world and are thus exogenous. Sector a produces capital goods, sector b produces consumption goods. Energy is imported. Technology depends only on the sector and is the same for the two regions. National and foreign products of a certain type are supposed to be perfect substitutes. Emissions are linked to energy consumption, and for the sake of simplicity, e denotes simultaneously energy and emissions. We assume that there exists an international tradable permits market where polluting firms can buy or sell permits at a given exogenous price.

2.1 Behavior of the firms

The technology of sector j $(j = a, b)$ of region i $(i = v, w)$ at date t $(t \geq 1)$ is described by the following CES production function :

$$y_{ijt} = A_{ijt}\left[\alpha_j k_{ijt}^{\nu} + [1-\alpha_j]\, e_{ijt}^{\nu}\right]^{\frac{\xi}{\nu}} \tag{1}$$

where y, k and e are production, capital and energy respectively and A is a coefficient that measures technological progress. α_j and $1-\alpha_j$ are the respective shares of capital and energy in sector j. We assume that the shares α_j satisfy $0 < \alpha_j < 1$. ξ measures the returns to scale. We also assume that $0 < \xi < 1$, so that the returns of the production function are decreasing. ν is the substitution parameter which determines the constant elasticity of substitution between capital and energy (ε_{ke}) through the relation $\varepsilon_{ke} = 1/[1-\nu]$. For ε_{ke} to be a positive and finite number, one must verify that $\nu < 1$. In order to obtain clear cut results, we assume that ξ and ν are the same for both sectors $j = a, b$. Hereafter, the case $\nu < 0$ will be referred to as the inputs complementarity case. Because $\xi < 1$, the production function is concave, which is needed for the optimization problem below to make sense.

In our framework, adoption of green technologies that reduce the emissions/production ratio are taken implicitly into account through substitution of capital to energy and through technical progress, i.e. an increase of A through capital accumulation (see hereafter).

The representative firm of sector j of region i is assumed to choose the flow of its energy consumption and investment in order to maximize the sum of its discounted profits :

$$\Pi_{ij} = \max_{\{e_{ijt}, \iota_{ijt}\}_{t\geq 1}} \sum_{t\geq 1} \frac{\pi_{ijt}}{[1+r]^t} \tag{2}$$

under the constraints that

$$\begin{aligned} k_{ijt} &= k_{ij,t-1}[1-\delta] + \iota_{ijt},\ t \geq 1 && (3) \\ \overline{e}_{ijt} &= \widetilde{e}_{ijt} + \lambda e_{ij,t-1},\ t \geq 1 && (4) \end{aligned}$$

where by definition

$$\pi_{ijt} = p_{jt} y_{ijt} - q_t e_{ijt} - p_{at}\iota_{ijt} + \tau_t\left[\overline{e}_{ijt} - e_{ijt}\right] \tag{5}$$

and where e_{ij0}, k_{ij0} and y_{ij0} are given. r is the (exogenous) positive discount rate. (3) is the familiar capital accumulation equation, where ι is investment and δ measures the depreciation rate of capital.[7] (5) defines π_{ijt} as the current profit of sector j of region i at date t, where p_j, q and τ are the prices of good j ($j = a, b$), energy and tradable permits respectively. Following Böringer and Lange (2005), (4) defines the permit endowment received by sector j of region i at date t ($\overline{e}_{ijt}$) as a linear function of its emissions of the previous period, where $\widetilde{e}_{ijt}, \lambda$ are given exogenous positive parameters.[8] Since the price of capital goods is used as the numéraire, $p_{at} = 1, \forall t \geq 1$. After substitution of (5), (3) and (4) in (2), the problem rewrites

$$
\begin{aligned}
& \max_{\{e_{ijt},k_{ijt}\}_{t\geq 1}} \sum_{t\geq 1} \frac{1}{[1+r]^t} \left[p_{jt}y_{ijt} - [q_t + \tau_t]\, e_{ijt} \right. \\
& \left. - [k_{ijt} - k_{ij,t-1}[1-\delta_j]] + \tau_t \left[\widetilde{e}_{ijt} + \lambda e_{ij,t-1}\right]\right] \\
= \; & \frac{1}{[1+r]} \left[k_{ij0}[1-\delta_j] + \tau_1 \left[\lambda e_{ij0}\right]\right] \\
& + \max_{\{e_{ijt},k_{ijt}\}_{t\geq 1}} \sum_{t\geq 1} \frac{1}{[1+r]^t} \left[p_{jt}y_{ijt} - \left[q_t + \tau_t - \tau_{t+1}\frac{\lambda}{1+r}\right] e_{ijt} \right. \\
& \left. - \left[1 - \frac{1-\delta_j}{1+r}\right] k_{ijt} + \tau_t \widetilde{e}_{ijt}\right] \\
= \; & C^t + \max_{\{e_{ijt},k_{ijt}\}_{t\geq 1}} \sum_{t\geq 1} \frac{1}{[1+r]^t} \left[p_{jt}y_{ijt} - \widetilde{q}_t e_{ijt} - \widetilde{p}_{jt} k_{ijt} + \tau_t \widetilde{e}_{ijt}\right] \qquad (6)
\end{aligned}
$$

where we define

$$\widetilde{p}_{jt} = \widetilde{p} = 1 - \frac{1-\delta}{1+r} = \frac{\delta + r}{1+r} \qquad (7)$$

as the *user cost of capital* of sector j at date t and

$$\widetilde{q}_t = q_t + \tau_t - \tau_{t+1}\frac{\lambda}{1+r} \qquad (8)$$

---

[7] For the sake of simplicity, we assume that the depreciation rate of capital is the same in both sectors. Nevertheless we are able to verify that most of our results are also valid in the case where the depreciation rate of capital varies across sectors.

[8] As Böhringer and Lange (2005) puts it, the feature that a firm accounts for the dependence of its future permit endowments on its emissions corresponds to emission-based rebating schemes of tax revenues. Efficient losses are then possible. The aim of these authors is to compute the parameters of the relation between endowments and emissions in order to minimize these losses. They show a.o. that the optimal values of these parameters depend on whether the permits market is open or not. Our aim being quite different, we will consider these parameters as exogenous.

as the *user cost of energy* of sector j at date t.

First order conditions lead to

$$\begin{aligned}
\frac{\partial \Pi_{ij}}{\partial k_{ijt}} &= \alpha_j p_{jt} \xi \frac{y_{ijt}}{\alpha_j k_{ijt}^{\nu} + [1-\alpha_j]\, e_{ijt}^{\nu}} k_{ijt}^{\nu-1} - \widetilde{p}_j = 0 \\
\frac{\partial \Pi_{ij}}{\partial e_{ijt}} &= [1-\alpha_j]\, p_{jt} \xi \frac{y_{ijt}}{\alpha_j k_{ijt}^{\nu} + [1-\alpha_j]\, e_{ijt}^{\nu}} e_{ijt}^{\nu-1} - \widetilde{q}_t = 0
\end{aligned}$$

which after some computations yields the following solutions

$$\begin{aligned}
e_{ijt} &= \left[[1-\alpha_j]\, A_{ijt} \xi \frac{p_{jt}}{\widetilde{q}_t} \left[\alpha_j \phi_{jt}^{\nu} + 1 - \alpha_j \right]^{\frac{\xi}{\nu}-1} \right]^{\frac{1}{1-\xi}} && (9) \\
k_{ijt} &= \phi_{jt} e_{ijt} && (10) \\
y_{ijt} &= A_{ijt} \left[\alpha_j \phi_{jt}^{\nu} + 1 - \alpha_j \right]^{\frac{\xi}{\nu}} e_{ijt}^{\xi} && (11)
\end{aligned}$$

where by definition

$$\phi_{jt} = \left[\frac{1-\alpha_j}{\alpha_j} \frac{\widetilde{p}}{\widetilde{q}_t} \right]^{\frac{1}{\nu-1}} \tag{12}$$

is the capital-energy ratio.

2.2 Endogenous growth and technical spillovers

One assumes that

$$A_{ijt} = \rho_t^{\gamma} \left[\theta_{jt} k_{ij,t-1} + [1-\theta_{jt}]\, K_{j,t-1} \right]^{\gamma} \tag{13}$$

where by definition, $K_{jt} = k_{wjt} + k_{vjt}$ is the capital of sector j at the country level. γ is such that $\xi + \gamma = 1$, i.e. global returns to scale are constant. ρ_t and θ_{jt} $(t \geq 1)$ are exogenous positive parameters. With respect to the spillover parameters θ_{jt}, we assume that $0 \leq \theta_{jt} < 1$ $(\forall t \geq 1)$ and $\lim_{t \to +\infty} \theta_{jt} = \overline{\theta_j} < 1$. (13) shows that the productivity factor of sector j of region i at time t depends not only on the capital of this sector inherited from the previous period, but also on the capital of the same sector of the other region. There is therefore an inter-regional technological spillover at the sector level. The spillover is intra-sectoral. Notice that the larger θ_{jt}, the lower the impact of the learning-by-investing accumulated in region w on technological progress in region v for sector j. We shall use this observation in some interpretations later on.

Given the previous assumptions, and given (9) and (10), one obtains

$$\begin{aligned} k_{ijt} &= \phi_{jt} A_{ijt}^{\frac{1}{1-\xi}} \left[[1-\alpha_j]\, \xi \frac{p_{jt}}{\widetilde{q}_t} \left[\alpha_j \phi_{jt}^{\nu} + 1 - \alpha_j\right]^{\frac{\xi}{\nu}-1} \right]^{\frac{1}{1-\xi}} \\ &= \zeta_{jt}\rho_t \left[\theta_{jt} k_{ij,t-1} + [1-\theta_{jt}]\, K_{j,t-1}\right] \\ &= \zeta_{jt}\rho_t \left[k_{ij,t-1} + [1-\theta_{jt}]\, k_{\widetilde{i}j,t-1}\right] \qquad (14) \end{aligned}$$

where $\widetilde{i}$ designates the other region and where

$$\begin{aligned} \zeta_{jt} &=_{def} \phi_{jt} \left[[1-\alpha_j]\, \xi \frac{p_{jt}}{\widetilde{q}_t} \left[\alpha_j \phi_{jt}^{\nu} + 1 - \alpha_j\right]^{\frac{\xi}{\nu}-1} \right]^{\frac{1}{1-\xi}} \\ &= \phi_{jt} \left[\alpha_j \phi_{jt}^{\nu} + 1 - \alpha_j\right]^{\frac{\xi-\nu}{\nu[1-\xi]}} \left[[1-\alpha_j]\, \xi \frac{p_{jt}}{\widetilde{q}_t} \right]^{\frac{1}{1-\xi}} \qquad (15) \end{aligned}$$

For each sector j, we consider the system:

$$\begin{aligned} k_{wjt} &= \zeta_{jt}\rho_t \left[k_{wj,t-1} + [1-\theta_{jt}]\, k_{vj,t-1}\right] \qquad (16) \\ k_{vjt} &= \zeta_{jt}\rho_t \left[k_{vj,t-1} + [1-\theta_{jt}]\, k_{wj,t-1}\right] \qquad (17) \end{aligned}$$

for $t \in \mathcal{T}$, k_{wj0} and k_{vj0} given.

Proposition 1 *The solutions to the system (16-17) can be expressed as:*

$$k_{wjt} = \frac{1}{2} \prod_{m=1}^{t} \{\zeta_{jm}\rho_{jm}\} \left\{ \left\{ [k_{wj0} + k_{vj0}] \prod_{m=1}^{t} [2-\theta_{jm}] \right\} + \left\{ [k_{wj0} - k_{vj0}] \prod_{m=1}^{t} \theta_{jm} \right\} \right\} \qquad (18)$$

$$k_{vjt} = \frac{1}{2} \prod_{m=1}^{t} \{\zeta_{jm}\rho_{jm}\} \left\{ \left\{ [k_{wj0} + k_{vj0}] \prod_{m=1}^{t} [2-\theta_{jm}] \right\} + \left\{ [k_{vj0} - k_{wj0}] \prod_{m=1}^{t} \theta_{jm} \right\} \right\} \qquad (19)$$

Proof. See Appendix 1. ■ .

It follows immediately that for a given sector j, and provided the two regions have the same initial endowment of capital in that sector, then their respective endowments of capital remain equal in all periods, that is:

$$k_{vjt} = k_{wjt} = \frac{1}{2} [k_{wj0} + k_{vj0}] \prod_{m=1}^{t} \zeta_{jm}\rho_m [2-\theta_{jm}]$$

By Proposition 1, one can write for Region i

$$k_{ijt} = \frac{1}{2}\left\{\prod_{m=1}^{t}\zeta_{jm}\rho_m\left[2-\theta_{jm}\right]\right\}\left\{k_{ij0}+k_{\tilde{i}j0}+\left[k_{ij0}-k_{\tilde{i}j0}\right]\prod_{m=1}^{t}\frac{\theta_{jm}}{2-\theta_{jm}}\right\} \tag{20}$$

Then :

Proposition 2 *Whatever the initial conditions and the exogenous variables' patterns, the regional capital stocks of the same sector converge to the same value asymptotically:*

$$\lim_{t\to+\infty}k_{wjt} = \lim_{t\to+\infty}k_{vjt} = \frac{1}{2}\left[k_{wj0}+k_{vj0}\right]\prod_{m=1}^{+\infty}\zeta_{jm}\rho_m\left[2-\theta_{jm}\right],\ j=a,b$$

Proof. See Appendix 2. ■

This strong result follows from the fact that except the initial sectoral endowment of capital, the two regions are identical: they face the same international prices and share the same technologies. In the presence of intra-sectoral spillovers, the divergence force coming from endogenous growth (namely, constant returns) is neutralized. Indeed, notice that if the parameters $\theta_{jt}=1$ for every t, then equations (18) and (19) would imply that the capital stocks of the two regions will diverge over time if the initial stocks are different. If this sequence of parameters is permanently strictly below 1, then such a divergence mechanism is dominated by intra-sectoral spillovers.

Given (20), one can express the growth rate of sector j of region i at time t as

$$g_{ijt} = \frac{k_{ijt}}{k_{ij,t-1}} = \zeta_{jt}\rho_t\left[2-\theta_{jt}\right]X_{ijt},\ i=v,w,\ j=a,b,\ t\geq 1 \tag{21}$$

where by definition

$$X_{ijt} = \frac{k_{ij0}+k_{\tilde{i}j0}+\left[k_{ij0}-k_{\tilde{i}j0}\right]\prod_{m=1}^{t}\frac{\theta_{jm}}{2-\theta_{jm}}}{k_{ij0}+k_{\tilde{i}j0}+\left[k_{ij0}-k_{\tilde{i}j0}\right]\prod_{m=1}^{t-1}\frac{\theta_{jm}}{2-\theta_{jm}}} \tag{22}$$

In the long term, g_{ijt} tends to $\zeta_{jt}\rho_t\left[2-\overline{\theta}_j\right]$, which as expected does not depend on i.

3 Impact of an environmental policy

3.1 Preliminaries

The baseline economy is characterized by the absence of environmental policy (EP), i.e. there are no permit endowments and the user cost of energy reduces to its price ($\widetilde{q}_t^B = q_t$). The baseline is thus characterized by the following growth rate for sector j of region i at time t :

$$g_{ijt}^B = \frac{k_{ijt}^B}{k_{ij,t-1}^B} = \zeta_{jt}^B \rho_t \left[2 - \theta_{jt}\right] X_{ijt} \tag{23}$$

where given (15) and (12),

$$\begin{aligned} \zeta_{jt}^B &= \phi_{jt}^B \left[\alpha_j \left(\phi_{jt}^B\right)^\nu + 1 - \alpha_j\right]^{\frac{\xi-\nu}{\nu[1-\xi]}} \left[\left[1 - \alpha_j\right] \xi \frac{p_{jt}}{q_t}\right]^{\frac{1}{1-\xi}} & (24) \\ \phi_{jt}^B &= \left[\frac{1-\alpha_j}{\alpha_j} \frac{\widetilde{p}_j}{q_t}\right]^{\frac{1}{\nu-1}} & (25) \end{aligned}$$

and where X_{ijt} is defined by (22). Therefore along the baseline, the user cost of energy reduces to the price of energy (the baseline is characterized by a sequence of permits prices equal to 0).

As we aim to study the impact of an EP across sectors and regions, we state the following important assumptions which fix our framework without any loss of generality:

Assumption 1 : *Sector a is more energy intensive than sector b*:

$$\alpha_a < \alpha_b \tag{26}$$

Assumption 2 : *Region w is initially more specialized in the production of good a than Region v*:

$$\frac{k_{wa0}}{k_{wb0}} > \frac{k_{va0}}{k_{vb0}} \tag{27}$$

We look at the impact of an EP characterized by a sequence of permits prices $\{\tau_t,\ t \geq 1\}$ and by permit endowments defined by (4). The burden sharing rule (4) assumes that a firm's current permit endowment depends on its emissions in the previous period. We qualify this dependence as the "endowment" effect. We first consider the case where this effect is not internalized by firms when they maximize their profits.[9] In such a case, one applies (4) with $\lambda = 0$ ($j = a, b$, $\forall t \geq 1$) and :

$$\overline{e}_{ijt} = \widetilde{e}_{ijt} = \eta e_{ij,t-1}, \tag{28}$$

where η is a positive exogenous parameter ($0 < \eta < 1$) and $e_{ij,t-1}$ are the emissions characterizing the EP at $t-1$. $\widetilde{e}_{ijt}$ is considered as exogenous by the firms when they solve problem (2), then given (8), one gets $\widetilde{q}_t = q_t + \tau_t$. In section 3.3, we will consider the alternative case where the "endowment" effect is internalized by firms.

In order to evaluate the impact of the EP, we proceed in successive steps. First, we start with the sectoral level. At this level, the impact of the EP with respect to the baseline (no policy) scenario is assessed in terms of (i) growth rates, (ii) capital stocks, and (iii) total revenues (including net permit endowments). Secondly, the analysis is extended to the regional level.

3.2 Impact at the sectoral level

3.2.1 Impact on the sectoral growth rates

Proposition 3 *The impact of the EP on the sectoral growth rates is the same in both regions:*

$$\frac{g_{wjt}}{g^B_{wjt}} = \frac{g_{vjt}}{g^B_{vjt}}, \ j = a, b \tag{29}$$

Proof. Given (21), (23), (15) and (24), it follows that

$$\frac{g_{ijt}}{g^B_{ijt}} = \frac{\zeta_{jt}}{\zeta^B_{jt}} = \frac{\phi_{jt}}{\phi^B_{jt}} \left[\frac{\alpha_j \phi^{\nu}_{jt} + 1 - \alpha_j}{\alpha_j \left(\phi^B_{jt}\right)^{\nu} + 1 - \alpha_j} \right]^{\frac{\xi-\nu}{\nu[1-\xi]}} \left[\frac{q_t}{\widetilde{q}_t} \right]^{\frac{1}{1-\xi}} \tag{30}$$

where ϕ_{jt} and ϕ^B_{jt} are defined by (12) and (25) respectively. The RHS does not depend on i, so the proposition follows immediately. ■

This result is very intuitive since the sectors j of both regions face the same exogenous prices and share the same technologies. The effect of EP on sectoral growth rates is much trickier as reflected in the following proposition.

Proposition 4 *The EP affects the sectoral growth rates as follows:*

$$\frac{g_{ijt}}{g^B_{ijt}} 1 \Leftrightarrow \nu\xi, \ i = v, w; \ j = a, b \tag{31}$$

---

[9] This could be justified if the rule applies at an aggregate level and if the firm is small enough and receives a fixed share of the total permits endowment.

Proof. See Appendix 3. ■

The proposition has several implications. First, since growth is induced by capital accumulation and as EP raises the cost of energy, capital accumulation and thus growth are negatively affected by EP under complementarity of energy and capital, that is when $\nu < 0$, which is the most realistic case. Second, when $\nu > 0$, capital accumulation and growth are still harmed by EP if the substitution parameter is low enough (here $\nu < \xi$). Otherwise when $\xi < \nu < 1$, EP will stimulate growth. Needless to say, given that the input factors are capital and energy, such a case is parametrically unrealistic and we shall abstract from it hereafter. We now compare the impact of the EP on the growth rates of both sectors.

Proposition 5 *If* $\nu < 0$ *then*

$$\frac{g_{iat}}{g_{iat}^{B}} < \frac{g_{ibt}}{g_{ibt}^{B}}, i = v, w \tag{32}$$

Proof. See Appendix 4. ■

In other words, under factor complementarity, the more energy intensive sector is more affected (relative to the baseline). The mechanisms behind this property are similar to those outlined just above. Two remarks are however in order. First of all, from (12), (15) and (21), one can easily verify that if $\nu < 0$, the sectoral growth rate is a negative function of the user cost of capital (i.e. $\partial g_{ijt}/\partial \widetilde{p} < 0$). On the other hand, one also verifies under the same condition that the lower the user cost of capital, the more the growth rate of a sector is affected by the EP. In words, as the production factors become increasingly complementary, a low user cost of capital promotes growth but also makes it more sensible to an increase of the user cost of energy. Second, similarly to the previous proposition, it should be underlined that the condition $\nu < 0$ is sufficient, but not necessary for the growth rate of the energy intensive sector to be more affected by the EP than the other sector's growth rate. On the other hand, this rather expected result does not hold for all values of ν higher than 0 [10].

---

[10] We have also checked that Proposition 3 and 4 are verified when $\widetilde{p}_a \neq \widetilde{p}_b$. Proposition 5 is also verified if $\widetilde{p}_a \leq \widetilde{p}_b$. But Proposition 5 does not hold for all possible values of $\widetilde{p}_a$ and $\widetilde{p}_b$.

3.2.2 Impact on the sectoral capital stock

We compare the impact of the EP on capital accumulation of the two sectors of a given region w.r.t. the baseline. Given (21) and (23), one has

$$k_{ijt} = k_{ij0} \prod_{m=1}^{t} g_{ijm} \text{ and } k_{ijt}^{B} = k_{ij0} \prod_{m=1}^{t} g_{ijm}^{B}$$

so that

$$\frac{k_{ijt}}{k_{ijt}^{B}} = \prod_{m=1}^{t} \frac{g_{ijm}}{g_{ijm}^{B}} \tag{33}$$

Then the two following propositions can be deduced straightforwardly from the properties already established for the growth rates in the previous section. Needless to say, the same economic mechanisms are active.

Proposition 6 *If* $\nu < 0$ *then*

$$\frac{k_{iat}}{k_{iat}^{B}} < \frac{k_{ibt}}{k_{ibt}^{B}}, i = v, w \tag{34}$$

Proof. This result follows immediately from Proposition 5. ■

Proposition 7 *The impact of the EP on the sectoral capital stocks is the same in both regions:*

$$\frac{k_{wjt}}{k_{wjt}^{B}} = \frac{k_{vjt}}{k_{vjt}^{B}},\ j = a, b \tag{35}$$

Proof. This result follows immediately from Proposition 3. ■

3.2.3 Impact on the sectoral revenues

We now compare the impacts of the EP on the sectoral revenues of the two sectors of a given region w.r.t. the baseline. The sectoral revenue is defined as the sum of the gross added value of the sector and the net endowment of permits. In our setting, the intermediate consumption is limited to the imported energy consumption[11]. Thus the sectoral revenue writes:

$$\begin{aligned} r_{ijt} &= p_{jt} y_{ijt} - q_t e_{ijt} + \tau_t \left[\overline{e}_{ijt} - e_{ijt} \right] \\ &= s_{ijt} + \tau_t \overline{e}_{ijt},\ i = v, w,\ j = a, b,\ t \geq 1 \end{aligned} \tag{36}$$

---

[11] Because we use the concept of gross added value, we ignore capital depreciation.

where production and energy consumption are defined by (9) and (11), $\overline{e}_{ijt}$ is defined by (4), and:

$$s_{ijt} = p_{jt}y_{ijt} - \widetilde{q}_t e_{ijt} \tag{37}$$

is the sectoral revenue *without* permit endowment. Along the baseline, $\widetilde{q}_t = q_t$ and there are no endowment of permits, implying

$$r^B_{ijt} = s^B_{ijt}.$$

We now check under which conditions it is verified that:

$$\frac{r_{iat}}{r^B_{iat}} < \frac{r_{ibt}}{r^B_{ibt}},\ i = v, w \tag{38}$$

First, it should be noted that:

$$\frac{r_{ijt}}{r^B_{ijt}} = \frac{s_{ijt} + \tau_t\overline{e}_{ijt}}{s^B_{ijt}} = \frac{s_{ijt}}{s^B_{ijt}} + \frac{\tau_t\overline{e}_{ijt}}{s^B_{ijt}} \tag{39}$$

It is clear that a sufficient condition for (38) to be satisfied is that the two following inequalities hold simultaneously:

$$\frac{s_{iat}}{s^B_{iat}} < \frac{s_{ibt}}{s^B_{ibt}} \tag{40}$$

$$\frac{\tau_t\overline{e}_{iat}}{s^B_{iat}} < \frac{\tau_t\overline{e}_{ibt}}{s^B_{ibt}} \tag{41}$$

Hereafter, we consider these two inequalities separately.

Sectoral revenues without permit endowments

We start our analysis by the ratios of the sectoral revenue without endowment terms $\frac{s_{ijt}}{s^B_{ijt}}$, $j = a, b$. Using the equations (9) to (11), and after tedious computations, one establishes that:

$$y_{ijt} = \frac{\omega_{jt}}{\phi_{jt}}k_{ijt}, \tag{42}$$

where

$$\omega_{jt} = \frac{\widetilde{q}_t}{p_{jt}}\frac{\alpha_j\phi^\nu_{jt} + 1 - \alpha_j}{\xi(1-\alpha_j)}. \tag{43}$$

We denote by ω^B_{jt} the equivalent expression for the baseline (with q_t replacing $\widetilde{q}_t$). Equations (10) and (42) in turn imply that:

$$s_{ijt} = \frac{k_{ijt}}{\phi_{jt}}\left[p_{jt}\omega_{jt} - \widetilde{q}_t\right] \tag{44}$$

$$s^B_{ijt} = \frac{k^B_{ijt}}{\phi^B_{jt}}\left[p_{jt}\omega^B_{jt} - q_t\right] \tag{45}$$

so that :

$$\frac{s_{ijt}}{s_{ijt}^B} = \frac{\phi_{jt}^B}{\phi_{jt}} \frac{k_{ijt}}{k_{ijt}^B} \frac{p_{jt}\omega_{jt} - \widetilde{q}_t}{p_{jt}\omega_{jt}^B - q_t}.$$

Because the first term $\frac{\phi_{jt}^B}{\phi_{jt}}$ only depends on the ratio $\frac{\widetilde{q}_t}{q_t}$, which is the same in both sectors, (40) reduces to :

$$\frac{k_{iat}}{k_{iat}^B} \frac{p_{at}\omega_{at} - \widetilde{q}_t}{p_{at}\omega_{at}^B - q_t} < \frac{k_{ibt}}{k_{ibt}^B} \frac{p_{bt}\omega_{bt} - \widetilde{q}_t}{p_{bt}\omega_{bt}^B - q_t} \tag{46}$$

The discrepancy between sectoral revenues without permit endowment can be attributed to two factors: the difference in capital accumulation via the terms $\frac{k_{ijt}}{k_{ijt}^B}$, already studied in Proposition 6, and the difference in the more complex terms $\frac{p_{jt}\omega_{jt} - \widetilde{q}_t}{p_{jt}\omega_{jt}^B - q_t}$, which reflect the differences in factor intensity via the term α_j and a priori also in prices p_{jt}. However, one can see that the latter effect vanishes as it only plays through the product $p_{jt}\omega_{jt}$ (since ω_{jt} is inversely proportional to p_{jt}). More concretely, by definition of ϕ_{jt}, equation (44) implies that the terms $p_{jt}\omega_{jt} - \widetilde{q}_t$ are value-added per unit of energy terms (without permit endowment here). Under an EP raising the price of energy, it is not clear at all why these terms will be more negatively affected in the more energy-intensive sector (relative to the baseline), and why factor complementarity should reinforce such an effect. Actually, the following proposition shows just the contrary.

Proposition 8 *Given that $\nu < 1$, we have:*

$$\frac{p_{at}\ \omega_{at} - \widetilde{q}_t}{p_{at}\ \omega_{at}^B - q_t} \frac{p_{bt}\ \omega_{bt} - \widetilde{q}_t}{p_{bt}\ \omega_{bt}^B - q_t} \Leftrightarrow \nu 0, \tag{47}$$

Proof. See Appendix 5. ■

It follows that when $\nu < 0$, the EP will have an ambiguous effect on the sectoral revenues without endowment since the effect through the terms $\frac{p_{jt}\ \omega_{jt} - \widetilde{q}_t}{p_{jt}\ \omega_{jt}^B - q_t}$ (the value-added per unit of energy effect) goes against the effect through the capital accumulation terms (the capital effect) already disentangled in Proposition 6.

We can now state the following result:

Proposition 9 *If $\nu < 0$ then*

$$\frac{s_{iat}}{s_{iat}^B} < \frac{s_{ibt}}{s_{ibt}^B} \tag{48}$$

for t large enough

Proof. See Appendix 6. ■

The result depicted in the last proposition is proved by showing that the value-added per unit of energy effect is dominated in the long term by the capital effect. Indeed, the ratio $\frac{k_{iat}k_{ibt}^B}{k_{iat}^B k_{ibt}}$ tends to 0 in the long run (this follows from Proposition 5) while the the ratio $\frac{p_{at}\omega_{at}-\widetilde{q}_t}{p_{at}\omega_{at}^B-q_t}\frac{p_{bt}\omega_{bt}^B-q_t}{p_{bt}\omega_{bt}-\widetilde{q}_t}$ remains bounded from below, thereby ensuring that (46) will be satisfied after some time. In the short run, the value-added of the energy-intensive sector (without permit endowments) might well be less harmed (relative to the baseline) as the capital stock effect might not be sizeable enough at this time horizon. What if permit endowments are accounted for?

Sectoral permit endowments

Now we focus on inequality (41). Let $\Lambda_{ijt} = \frac{\tau_t\,\overline{e}_{ijt}}{s_{ijt}^B}$. As we will see in a minute, these transfer terms will make the problem even trickier. Given that $\overline{e}_{ijt}$ is defined by (28) and because of the optimality condition (10), we have:

$$\Lambda_{ijt} = \frac{\eta\tau_t}{p_{jt}\omega_{jt}^B - q_t}\,\frac{k_{ijt-1}}{\phi_{jt-1}}\,\frac{\phi_{jt}^B}{k_{ijt}^B},$$

which, given (21), (12) and (25) can be rewritten as:

$$\begin{aligned}\Lambda_{ijt} &= \frac{\eta\tau_t}{p_{jt}\omega_{jt}^B - q_t}\,\frac{k_{ijt-1}}{k_{ijt}}\,\frac{k_{ijt}}{k_{ijt}^B}\,\frac{\phi_{jt}}{\phi_{jt-1}}\,\frac{\phi_{jt}^B}{\phi_{jt}}. &(49)\\ &= \frac{\eta\tau_t}{p_{jt}\omega_{jt}^B - q_t}\frac{1}{g_{ijt}}\frac{k_{ijt}}{k_{ijt}^B}\left[\frac{\widetilde{q}_t}{\widetilde{q}_{t-1}}\right]^{\frac{1}{1-\nu}}\left[\frac{q_t}{\widetilde{q}_t}\right]^{\frac{1}{1-\nu}} &(50)\end{aligned}$$

Therefore the transfer term is quite complicated since it can be decomposed into the product of five different terms. Fortunately, the fourth and fifth terms are sector-independent and thus cancel when one considers the inequality (41). The impact of the EP through the third term, $\frac{k_{ijt}}{k_{ijt}^B}$, is depicted in Proposition 6. Unfortunately, things are less clear if we account for the first term, $\frac{\eta\tau_t}{p_{jt}\omega_{jt}^B-q_t}$, which appeared above in the analysis of sectoral revenues without endowment, and for the second term, $\frac{k_{ijt-1}}{k_{ijt}} = \frac{1}{g_{ijt}}$, which derives from the grand-fathering rule adopted. In short, we cannot bring out an immediate conclusion on the transfer term Λ_{ijt} which can be or not favorable to the less energy-intensive sector for a fixed date t. However, similarly to our treatment for the sectoral revenue without endowment, we can precise the conditions under which that transfer term is favorable to the less energy-intensive sector for t large enough, even though it is already obvious that everything can happen in the short-run.

Proposition 10 *If (i) $\nu < 0$ and (ii) the ratio $\frac{p_{at}}{p_{bt}}$ does not tend to 0, then*

$$\frac{\tau_t \; \overline{e}_{iat}}{s^B_{iat}} < \frac{\tau_t \; \overline{e}_{ibt}}{s^B_{ibt}} \tag{51}$$

for t large enough

Proof. See Appendix 7. ■

The proof follows the same reasoning as for Proposition 9. But in contrast to what happens with the sectoral revenues without endowment, sectoral prices p_{jt} can potentially influence the last inequality through the terms ζ_{jt} in (21) appearing in the transfer component of the sectoral revenues comparison. Proposition 10 shows clearly that it is not the case: For any relative price $\frac{p_{at}}{p_{bt}} = \frac{1}{p_{bt}}$ which does not go to zero asymptotically, that is for any sequence of prices p_{bt} which does not go to infinity, the transfer terms rank in the "right" way under factor complementarity. This seems a minimal requirement in a framework like ours, Proposition 10 is therefore a quite robust asymptotic finding.

Finally, we reconsider inequality (38):

Proposition 11 *(i) If $\nu < 0$ and the ratio $\frac{p_{at}}{p_{bt}}$ does not tend to 0, or (ii) if $\nu < 0$ and the ratio $\frac{\tau_t}{q_t}$ is sufficiently small, then:*

$$\frac{r_{iat}}{r^B_{iat}} < \frac{r_{ibt}}{r^B_{ibt}} \tag{52}$$

for t large enough.

Proof. Result (i) follows immediately from (39) and Propositions 9 and 10. The proof of Result (ii) is in Appendix 8. ■

Result (ii) can be obtained when (40) is satisfied, while (41) is not. Consider the RHS of (36). Given (43) and (44), s_{ijt} is proportional to the user cost of energy $\widetilde{q}_t = q_t + \tau_t$, $s^B_{ijt}$is proportional to the price of energy q_t, while the permit endowment term $\tau_t \overline{e}_{ijt}$ is obviously proportional to the price of permits τ_t. If the ratio $\frac{\tau_t}{q_t}$ is small, $\frac{\tau_t}{\widetilde{q}_t}$is also small, and it is then intuitive that the term $\frac{s_{ijt}}{s^B_{ijt}}$ dominates the term $\frac{\tau_t \overline{e}_{ijt}}{s^B_{ijt}}$ in (39). Thus (52) follows after some time, given Proposition 9.

3.3 Internalizing the "endowment" effect

So far the impact of the EP has been analyzed under the assumption that the "endowment" effect is not internalized by firms (the permit endowments are given by (28) and $\widetilde{q}_t = q_t + \tau_t$). We now consider the alternative case where the "endowment" effect is internalized by firms. Formally, one applies (4) with $\widetilde{e}_{ijt} = 0$ and

$$\overline{e}_{ijt} = \lambda e_{ij,t-1} \tag{53}$$

where $0 < \lambda < 1$ and $e_{ij,t-1}$ are the emissions characterizing the EP at $t-1$. $\overline{e}_{ijt}$ is considered as endogenous by the firms when they solve problem (2), then given (8), $\widetilde{q}_t = q_t + \tau_t - \tau_{t+1}\frac{\lambda}{1+r}$.

In this case, the "endowment" effect translates into a decrease of the user cost of energy w.r.t. the case where this effect is not internalized. Nevertheless we make the reasonable assumption that the EP has the final effect to increase the user cost of energy. Formally :

Assumption 3 : λ is sufficiently small so that :

$$\tau_t - \tau_{t+1}\frac{\lambda}{1+r} > 0,\ j = a, b,\ \forall t \geq 1$$

In words, the effect of today's energy consumption on tomorrow's permit endowment is never sufficient to counteract the direct increase of the total cost of energy through the permits price.

Then, given (53) and the above assumption, one verifies easily that Propositions 3 to 11 follow again by a similar reasoning. It appears that the fact that firms anticipate the endowment effect or not does not modify our results.

3.4 Impact at the regional level

3.4.1 Specialization of the regions

Let us define the *specialization index* of Region i ($i = v, w$) at time t by the ratio:

$$\chi_{it} = \frac{k_{iat}}{k_{ibt}} \tag{54}$$

We also define the *spread of specialization index* at time t by the ratio of the specialization indexes of the two regions:

$$\sigma_t = \frac{\chi_{wt}}{\chi_{vt}} = \frac{k_{wat}}{k_{wbt}}\frac{k_{vbt}}{k_{vat}}$$

The purpose of the present subsection is to study the evolution of the regions' specialization through time. Using (20), we have:

$$\chi_{it} = \frac{k_{iat}}{k_{ibt}} = \frac{\left\{\prod_{m=1}^{t} \zeta_{am}\left[2-\theta_{am}\right]\right\}\left\{k_{ia0} + k_{\tilde{i}a0} + \left[k_{ia0} - k_{\tilde{i}a0}\right]\prod_{m=1}^{t}\frac{\theta_{am}}{2-\theta_{am}}\right\}}{\left\{\prod_{m=1}^{t} \zeta_{bm}\left[2-\theta_{bm}\right]\right\}\left\{k_{ib0} + k_{\tilde{i}b0} + \left[k_{ib0} - k_{\tilde{i}b0}\right]\prod_{m=1}^{t}\frac{\theta_{bm}}{2-\theta_{bm}}\right\}}, \ i = v, w$$

and

$$\sigma_t = \frac{\left\{k_{wa0} + k_{va0} + \left[k_{wa0} - k_{va0}\right]\prod_{m=1}^{t}\frac{\theta_{am}}{2-\theta_{am}}\right\}\left\{k_{wb0} + k_{vb0} + \left[k_{vb0} - k_{wb0}\right]\prod_{m=1}^{t}\frac{\theta_{bm}}{2-\theta_{bm}}\right\}}{\left\{k_{wb0} + k_{vb0} + \left[k_{wb0} - k_{vb0}\right]\prod_{m=1}^{t}\frac{\theta_{bm}}{2-\theta_{bm}}\right\}\left\{k_{wa0} + k_{va0} + \left[k_{va0} - k_{wa0}\right]\prod_{m=1}^{t}\frac{\theta_{am}}{2-\theta_{am}}\right\}} \tag{55}$$

One observes that in our set-up the spread of specialization index depends only on the initial stocks of capital and on the spillovers parameters that are exogenous. This property derives from two features of our setting. First of all, the specialization index is defined in terms of capital stocks: if it were defined in terms of value-added, prices would show up. Second, the assumption that the sectoral technologies are the same in all regions is essential in getting the prices out of the specialization index as one can infer from the computation of σ_t just above. Given this property, the latter index will not be affected by the environmental policies considered. This does not mean that the specialization index of a region (defined by (54)) does not change under an environmental policy w.r.t. the baseline. It means that the specialization indexes of the two regions are affected identically such that their spread remains unchanged.

In the *long run*, these formulas imply the following properties:

$$\lim_{t\to+\infty} \chi_{it} = \frac{K_{a0}}{K_{b0}}\left[\prod_{m=1}^{+\infty}\frac{\zeta_{am}}{\zeta_{bm}}\right], \ i = v, w \tag{56}$$

and

$$\lim_{t\to+\infty} \sigma_t = 1 \tag{57}$$

This result follows immediately from Proposition 2. Equation (56) shows that in the long run the regional specialization index reflects the initial specialization index at the *national* level and the exogenous patterns of prices (through the parameters ζ_{jm} (see (15)), which interact multiplicatively in our model.

Assume that $\sigma_0 > 1$ (i.e. Region w is more specialized in the production of the capital good). But the preceding result does not imply that σ_t decreases monotonously from $\sigma_0 > 1$ to $\sigma_\infty = 1$, as will be shown in the following subsection.

3.4.2 Impact on the regional revenues

The total revenue (i.e. after transfers) of region i $(i = v, w)$ at time t writes:

$$R_{it} = r_{iat} + r_{ibt}, \;\; i = v, w$$

The impact of the EP on the total revenue of region i can be measured by the ratio:

$$\frac{R_{it}}{R_{it}^B} = \frac{r_{iat}}{r_{iat}^B}\frac{s_{iat}^B}{S_{it}^B} + \frac{r_{ibt}}{r_{ibt}^B}\left[1 - \frac{s_{iat}^B}{S_{it}^B}\right]$$

where we have made use of the fact that along the baseline, $r_{ijt}^B = s_{ijt}^B$ $(j = a, b) \Rightarrow R_{it}^B = S_{it}^B = s_{iat} + s_{ibt}$ $(i = v, w; \; t \geq 1)$. The share of sector a in region i's regional product at time t at the baseline (s_{iat}^B / S_{it}^B) writes, given (43) and (45):

$$\frac{s_{iat}^B}{S_{it}^B} = \frac{1}{1 + \frac{1-\alpha_a}{1-\alpha_b}\frac{\alpha_b\left(\phi_{bt}^B\right)^\nu + [1-\alpha_b][1-\xi]}{\alpha_a\left(\phi_{at}^B\right)^\nu + [1-\alpha_a][1-\xi]}\frac{\phi_{at}^B}{\phi_{bt}^B}\frac{k_{ibt}^B}{k_{iat}^B}} \tag{58}$$

This share is thus positively related to the specialization index of region i along the baseline : $\chi_{it}^B = k_{iat}^B / k_{ibt}^B$.

We want to check under which conditions the inequality

$$\frac{R_{wt}}{R_{wt}^B} < \frac{R_{vt}}{R_{vt}^B} \tag{59}$$

is satisfied. If $\frac{r_{iat}}{r_{iat}^B} < \frac{r_{ibt}}{r_{ibt}^B}$ is verified, a sufficient condition ensuring (59) is that $\frac{s_{wat}^B}{S_{wt}^B} \geq \frac{s_{vat}^B}{S_{vt}^B}$, or given (58), that $\frac{k_{wbt}^B}{k_{wat}^B} \geq \frac{k_{vbt}^B}{k_{vat}^B} \Leftrightarrow \sigma_t \geq 1$ [12]. There should not be any inversion of specialization at date t w.r.t. date 0.

In this respect, we have the following result:

Proposition 12 *The spread of specialization index will not be reversed in period* t *w.r.t. period* 0 *(i.e.* $\sigma_0 > 1$ *and* $\sigma_t > 1$*), depending on the ratio of the spillover parameters* θ_{bt}/θ_{at} $(t \geq 1)$ *and on the initial capital endowments.*

Proof. Given (55), it is easy to verify that $\sigma_t > 1$ implies that :

$$[k_{wb0} + k_{vb0}]\,[k_{wa0} - k_{va0}] \prod_{m=1}^{t} \frac{\theta_{am}}{2 - \theta_{am}} > [k_{wa0} + k_{va0}]\,[k_{wb0} - k_{vb0}] \prod_{m=1}^{t} \frac{\theta_{bm}}{2 - \theta_{bm}}$$

---

[12] Remember that the spread of specialization index is not modified by the environmental policy.

Two cases emerge :
(a) $k_{wb0} - k_{vb0} > 0$: it follows that $\sigma_t > 1$ iff:

$$\frac{[k_{wb0} + k_{vb0}]\,[k_{wa0} - k_{va0}]}{[k_{wa0} + k_{va0}]\,[k_{wb0} - k_{vb0}]} > \prod_{m=1}^{t} \frac{\frac{\theta_{bm}}{2-\theta_{bm}}}{\frac{\theta_{am}}{2-\theta_{am}}}$$

From assumption (27) it follows that $k_{wa0} > k_{va0}$. The sequence $\{\theta_{at},\ t \geq 1\}$ must be in "average" high enough w.r.t. the sequence $\{\theta_{bt},\ t \geq 1\}$. This implies that in the long term, i.e. when the sequences are close to their limit values $\overline{\theta}_j$ $(j = a, b)$, the above inequality implies that the ratio $\overline{\theta}_b/\overline{\theta}_a$ is low enough.
(b) $k_{wb0} - k_{vb0} < 0$: it follows that $\sigma_t > 1$ iff:

$$\frac{[k_{wb0} + k_{vb0}]\,[k_{wa0} - k_{va0}]}{[k_{wa0} + k_{va0}]\,[k_{wb0} - k_{vb0}]} < \prod_{m=1}^{t} \frac{\frac{\theta_{bm}}{2-\theta_{bm}}}{\frac{\theta_{am}}{2-\theta_{am}}}$$

If $k_{wa0} - k_{va0} < 0$, then the sequence $\{\theta_{at},\ t \geq 1\}$ must be in "average" low enough w.r.t. the sequence $\{\theta_{bt},\ t \geq 1\}$. This implies that in the long term, i.e. when the sequences are close to their limit values $\overline{\theta}_j$ $(j = a, b)$, the above inequality implies that the ratio $\overline{\theta}_b/\overline{\theta}_a$ is high enough. If $k_{wa0} - k_{va0} > 0$, the regions have opposite specializations (i.e. $k_{wa0} > k_{va0}$ and $k_{wb0} < k_{vb0}$), then the above inequality is necessarily satisfied whatever the spillover parameters.
■

In summary, the EP affects more the regional product of the Region w at date t if the two following conditions are satisfied:
- the energy sector is more affected by the EP than the other sector (i.e. $r_{iat}/r^B_{iat} < r_{ibt}/r^B_{ibt}$);
- Region w is more specialized in the energy intensive sector 1 at date t. Given Assumption 2, this supposes that there is no inversion of specialization w.r.t. the initial period ($t = 0$);

OR if these two conditions are *both* invalidated.

Regarding the Belgian situation, one has $k_{wb0} < k_{vb0}$ (where w is Wallonia and v is Flanders), so that case (b) above applies. Because it is generally expected that the technological spillovers are higher in the capital good sector ($1 - \theta_{at} \geq 1 - \theta_{bt} \Longrightarrow \theta_{at} \leq \theta_{bt},\ t \geq 1$), one has an indication that there will be no inversion of specialization (at least after some time), so that Wallonia is likely to be more affected than Flanders by an EP such as studied in this paper if sector a (the energy intensive sector) remains more burdened in the long run.

3.5 Summing up: Are ERA and ERB so obvious?

We now summarize the principal results obtained and assess to which extent the statements ERA and ERB are corroborated.

First, at the sectoral level :

(a) in terms of growth rates, the energy intensive sector (the capital good sector) is more burdened by the EP than the other sector (the consumption good sector) if the production factors are complementary, that is if the substitution parameter (ν) is lower than 0. This is true at any period.

(b) in terms of capital stocks, the energy intensive sector is more burdened by the EP than the other sector if $\nu < 0$. This is true at any period.

(c) in terms of total revenue (that is taking account of the net permit endowment of the sector determined by an "emission-based grand-fathering" sharing rule) :

- everything can happen in the short term;
- in the long term, the energy intensive sector is more burdened by the EP than the other sector if $\nu < 0$ and, either (i) the relative output price of the energy intensive sector p_{at}/p_{bt}) does not tend to 0 in the long run, or (ii) the ratio τ_t/q_t is sufficiently small.

Making the link with the ERA presented in the introduction, one observes that this result holds when considering capital accumulation (whether in terms of growth rate or in terms of capital stock) *if* the production factors are complementary. Under factor substitution, ERA is ruled out if the elasticity of substitution is large enough. In terms of total revenue, it could be invalidated in the short term, and even in the long term if the ratio p_{at}/p_{bt} tends to 0.

Secondly, at the regional level :

(a) starting with different specializations, the two regions converge to the same specialization (measured by the ratio of the capital stocks of their respective sectors), but not necessarily in a monotonic way. Conditions are established under which the spread of specialization, which depends on the initial capital endowments and on the technological spillovers, might be reversed.

(b) in terms of total regional revenue (equal to the sum of the sectoral total revenues), the region specialized in the energy intensive sector is more affected by the EP than the other region *if*

- the energy intensive sector is more burdened than the other sector AND there is no inversion of specialization;
- the energy intensive sector is less burdened than the other sector AND there is inversion of specialization.

Making the link with the ERB presented in the introduction, one observes that this result does not preclude the situation where the region initially more affected by the EP is less affected in the long run.

However one also observes that translated in the framework of the Belgian debate, our analysis suggests that there will be no inversion of specialization, so that Wallonia is likely to be more affected than Flanders by environmental policies as modeled in this paper, not only in the short run (as in Germain et al., 2006) but also in the long run.

4 Conclusion

The model presented in this paper has been designed to study the burden sharing of pollution abatement in the context of a Kyoto-like protocol in a multi-regional multi-sectoral economy. In order to get the dynamic picture, we have considered time-dependent intra-sectoral spillovers across regions and learning-by-investing in each sector. In such a context, we have disentangled the main price-based and quantity-based mechanisms which determine the impact of environmental policy at different levels (sectoral and regional revenues notably). Within this framework, we have been able to extract some qualitative predictions for a small multi-regional country like Belgium. Nonetheless, to refine some of our conclusions, a more quantitative assessment is needed, and this would require a rigorous calibration of the model, including the exogenous price processes involved. A major difficulty comes from the fact that some processes like the price of pollution permits are not very well known given the short historical record. Alternatively, some reasonable scenarios could be considered.

On another hand, our model relies on some important simplifying assumptions, For instance, we have considered a small open economy where all prices are exogenous. Another assumption is that technologies are the same in both regions, and that these regions differ only in their initial relative endowments of capital. Production depends only on two factors, capital and (fossil) energy, and technology differs among sectors only at the level of the factor shares[13]. Further lines of research would be to assess the importance of these assumptions for our results.

Finally, we have only considered a dynamic “emission-based grand-fathering” sharing rule. Another possible line of interest would be to study other sharing rules, eventually designed to share the burden in a desired way.

---

[13] However, as argued in the paper, some of our results remain valid when the user cost of capital differs between sectors.

5 Appendix

5.1 Proof of Proposition 1

The system (16-17) can be rewritten in a planar stacked form :

$$\mathbf{K}_{jt} = \zeta_{jt}\rho_t \mathbf{A}_{jt}\mathbf{K}_{j,t-1} \tag{60}$$

where

$$\mathbf{A}_{jt} = \begin{bmatrix} 1 & 1-\theta_{jt} \\ 1-\theta_{jt} & 1 \end{bmatrix}$$

and

$$\mathbf{K}_{jt} = \begin{bmatrix} k_{wjt} \\ k_{vjt} \end{bmatrix}$$

The eigenvalues of $\mathbf{A}_{jt}$ are θ_{jt} and $2-\theta_{jt}$. Denote $\mathbf{P} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ and $\mathbf{D}_{jm} = \zeta_{jm}\rho_m \begin{bmatrix} 2-\theta_{jm} & 0 \\ 0 & \theta_{jm} \end{bmatrix}$. It is easy to check that the vector $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ is an eigenvector of $\mathbf{A}_{jt}$ associated with the eigenvalue $2-\theta_{jt}$, $\forall t \geq 1$. The same can be said about the vector $\begin{bmatrix} 1 \\ -1 \end{bmatrix}$ and the eigenvalue θ_{jt}. Therefore the eigenvectors are time independent. It follows that

$$\mathbf{K}_{jt} = \zeta_{jt}\rho_t \mathbf{P} \begin{bmatrix} 2-\theta_{jt} & 0 \\ 0 & \theta_{jt} \end{bmatrix} \mathbf{P}^{-1}\mathbf{K}_{j,t-1}$$

Then elementary backward successive substitutions leads to the solution to the system (60) :

$$\mathbf{K}_{jt} = \mathbf{P}\left[\prod_{m=1}^{t} \mathbf{D}_{jm}\right]\mathbf{P}^{-1}\mathbf{K}_{j0} \tag{61}$$

Then noticing that $\mathbf{P}^{-1} = \mathbf{P}/2$, one obtains (18) and (19).

5.2 Proof of Proposition 2

By Proposition 1, one can write for Region i :

$$k_{ijt} = \frac{1}{2}\left\{\prod_{m=1}^{t} \zeta_{jm}\rho_m\left[2-\theta_{jm}\right]\right\}\left\{k_{ij0} + k_{\widetilde{i}j0} + \left[k_{ij0} - k_{\widetilde{i}j0}\right]\prod_{m=1}^{t}\frac{\theta_{jm}}{2-\theta_{jm}}\right\}$$

where $\widetilde{i}$ is the other region. Given that by assumption, the sequence θ_{jt} is such that $0 \leq \theta_{jt} < 1$ and $\lim_{t\to+\infty} = \overline{\theta_j} < 1$, we have : $\frac{\theta_{jm}}{2-\theta_{jm}} < 1$, $\forall m \geq 1$, so that the sequence $\omega_{jt} = \prod_{m=1}^{t} \frac{\theta_{jm}}{2-\theta_{jm}}$ is strictly decreasing, and since it is bounded, it is converging. Notice that ω_{jt} is asymptotically geometric with coefficient $\frac{\bar{\theta}_j}{2-\bar{\theta}_j} < 1$, which implies that $\lim_{t\to+\infty} \omega_{jt} = 0$.

5.3 Proof of Proposition 3

Given (30), (31) can be rewritten :

$$\frac{g_{ijt}}{g_{ijt}^B} = \frac{F_j(\widetilde{q}_t)}{F_j(q_t)} \tag{62}$$

where by definition $F_j(x) = \frac{\phi_j(x)\left[\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j\right]^{\frac{\xi-\nu}{\nu[1-\xi]}}}{x^{\frac{1}{1-\xi}}}$ and $\phi_j(x) = \left[\frac{1-\alpha_j}{\alpha_j}\frac{\widetilde{p}_j}{x}\right]^{\frac{1}{\nu-1}}$. Let us take the total differential of $\ln(F_j(x))$ and of $\ln(\phi_j(x))$:

$$\frac{dF_j}{F_j} = \frac{d\phi_j}{\phi_j} + \frac{\xi-\nu}{\nu\,[1-\xi]} \frac{\alpha_j \nu \phi_j^{\nu-1}(x) d\phi_j}{\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j} - \frac{1}{1-\xi}\frac{dx}{x} \tag{63}$$

$$\frac{d\phi_j}{\phi_j} = \frac{1}{1-\nu}\frac{dx}{x} \tag{64}$$

Using (64) to substitute $d\phi_j/\phi_j$ in (63), one obtains :

$$\frac{dF_j}{F_j} = \frac{1}{1-\nu}\frac{dx}{x} + \frac{\xi-\nu}{[1-\xi]\,[1-\nu]} \frac{\alpha_j \phi_j^{\nu}(x)}{\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j}\frac{dx}{x} - \frac{1}{1-\xi}\frac{dx}{x}$$

Thus the elasticity of F_j w.r.t. x writes :

$$\begin{aligned}
\varepsilon_{F_j,x} &=_{def} \frac{x}{F_j}\frac{dF_j}{dx} = \frac{1}{1-\nu} + \frac{\xi-\nu}{[1-\xi]\,[1-\nu]} \frac{\alpha_j \phi_j^{\nu}(x)}{\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j} - \frac{1}{1-\xi} \\
&= \frac{\xi-\nu}{[1-\xi]\,[1-\nu]}\left[-1 + \frac{\alpha_j \phi_j^{\nu}(x)}{\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j}\right] \\
&= \frac{\nu-\xi}{[1-\xi]\,[1-\nu]} \frac{1-\alpha_j}{\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j}
\end{aligned}$$

Because $\xi, \nu < 1, 0 < \alpha_j < 1$ (by assumption) and $\alpha_j \phi_j^{\nu}(x) + 1 - \alpha_j > 0$, the sign of $\varepsilon_{F_j,x}$ is the sign of $\nu - \xi$. Given that $\widetilde{q}_t = q_t + \tau_t > q_t$ and that the sign of $F_j'(x)$ is the same as the sign of $\varepsilon_{F_j,x}$, the thesis follows.

5.4 Proof of Proposition 4

Given (30), (32) reduces to :

$$\frac{\phi_{at}}{\phi_{at}^B}\left[\frac{\alpha_a\phi_{at}^{\nu}+1-\alpha_a}{\alpha_a\left(\phi_{at}^B\right)^{\nu}+1-\alpha_a}\right]^{\frac{\xi-\nu}{\nu[1-\xi]}}<\frac{\phi_{bt}}{\phi_{bt}^B}\left[\frac{\alpha_b\phi_{bt}^{\nu}+1-\alpha_b}{\alpha_b\left(\phi_{bt}^B\right)^{\nu}+1-\alpha_b}\right]^{\frac{\xi-\nu}{\nu[1-\xi]}} \tag{65}$$

Given (12) and (25), $\frac{\phi_{at}}{\phi_{at}^B}=\frac{\phi_{bt}}{\phi_{bt}^B}=\left[\frac{q_t}{\widetilde{q}_t}\right]^{\frac{1}{\nu-1}}>0$. Because $\nu<0$, (65) leads to :

$$\frac{\alpha_a\phi_{at}^{\nu}+1-\alpha_a}{\alpha_a\left(\phi_{at}^B\right)^{\nu}+1-\alpha_a}>\frac{\alpha_b\phi_{bt}^{\nu}+1-\alpha_b}{\alpha_b\left(\phi_{bt}^B\right)^{\nu}+1-\alpha_b}$$

By using again (12) and (25), one obtains :

$$\frac{\alpha_a\left[\frac{1-\alpha_a}{\alpha_a}\frac{\widetilde{p}}{\widetilde{q}_t}\right]^{\frac{\nu}{\nu-1}}+1-\alpha_a}{\alpha_a\left[\frac{1-\alpha_a}{\alpha_a}\frac{\widetilde{p}}{q_t}\right]^{\frac{\nu}{\nu-1}}+1-\alpha_a}>\frac{\alpha_b\left[\frac{1-\alpha_b}{\alpha_b}\frac{\widetilde{p}}{\widetilde{q}_t}\right]^{\frac{\nu}{\nu-1}}+1-\alpha_b}{\alpha_b\left[\frac{1-\alpha_b}{\alpha_b}\frac{\widetilde{p}}{q_t}\right]^{\frac{\nu}{\nu-1}}+1-\alpha_b}$$

Let $B_j=\left[\frac{\alpha_j}{1-\alpha_j}\right]^{\frac{1}{1-\nu}}$ and $F(x)=\frac{\left[\frac{\widetilde{p}}{\widetilde{q}_t}\right]^{\frac{\nu}{\nu-1}}x+1}{\left[\frac{\widetilde{p}}{q_t}\right]^{\frac{\nu}{\nu-1}}x+1}$. Then the last inequality can be rewritten :Res

$$F(B_a)>F(B_b) \tag{66}$$

Now $F'(x)=\frac{\left[\frac{\widetilde{p}}{\widetilde{q}_t}\right]^{\frac{\nu}{\nu-1}}-\left[\frac{\widetilde{p}}{q_t}\right]^{\frac{\nu}{\nu-1}}}{\left[\left[\frac{\widetilde{p}}{q_t}\right]^{\frac{\nu}{\nu-1}}x+1\right]^2}<0\Leftarrow\widetilde{q}_t>q_t$ and $\nu<0$. Then (66) must be verified because $B_a<B_b$, which follows from Assumption 1.

5.5 Proof of Proposition 8

Given the expression of the terms ω_{jt} (cfr. (43)), the sectoral prices p_{jt} will immediately vanish when performing the products $p_{jt}\omega_{jt}$. After some simple algebraic operations,

$$\frac{p_{at}\,\omega_{at}-\widetilde{q}_t}{p_{at}\,\omega_{at}^B-q_t}\frac{p_{bt}\,\omega_{bt}-\widetilde{q}_t}{p_{bt}\,\omega_{bt}^B-q_t}$$

can be rewritten

$$u_t(X_a)=\frac{\left(\frac{\widetilde{p}}{\widetilde{q}_t}\right)^{\frac{\nu}{\nu-1}}X_a+1-\xi}{\left(\frac{\widetilde{p}}{q_t}\right)^{\frac{\nu}{\nu-1}}X_a+1-\xi}\frac{\left(\frac{\widetilde{p}}{\widetilde{q}_t}\right)^{\frac{\nu}{\nu-1}}X_b+1-\xi}{\left(\frac{\widetilde{p}}{q_t}\right)^{\frac{\nu}{\nu-1}}X_b+1-\xi}=u_t(X_b)$$

where

$$X_j = \left(\frac{1-\alpha_j}{\alpha_j}\right)^{\frac{1}{\nu-1}}.$$

One verifies that

$$u_t'(X) \sim \left(\frac{\widetilde{p}}{\widetilde{q}_t}\right)^{\frac{\nu}{\nu-1}} - \left(\frac{\widetilde{p}}{q_t}\right)^{\frac{\nu}{\nu-1}}$$

Then, since $q_t < \widetilde{q}_t$, we have:

$$\begin{array}{rcl} u_t'(X) & < & 0 \text{ iff } \nu < 0 \\ u_t'(X) & = & 0 \text{ iff } \nu = 0 \\ u_t'(X) & > & 0 \text{ iff } 0 < \nu < 1 \end{array}$$

Since X_j is increasing in α_j when $\nu < 1$, $\alpha_a < \alpha_b \Rightarrow X_a < X_b$. Then (47) follows.

5.6 Proof of Proposition 9

Given (10), (42) and (43), (37) becomes :

$$s_{ijt} = p_{jt}y_{jt} - \widetilde{q}_t e_{ijt} = \left[\frac{\alpha_j \phi_{jt}^{\nu} + 1 - \alpha_j}{\xi\left[1-\alpha_j\right]} - 1\right] \widetilde{q}_t \frac{k_{ijt}}{\phi_{jt}}$$

where ϕ_{jt} is defined by (12). Equivalently, for the baseline, we have:

$$s_{ijt}^B = p_{jt}y_{jt}^B - q_t e_{ijt}^B = \left[\frac{\alpha_j \left(\phi_{jt}^B\right)^{\nu} + 1 - \alpha_j}{\xi\left[1-\alpha_j\right]} - 1\right] q_t \frac{k_{ijt}^B}{\phi_{jt}^B}$$

where ϕ_{jt}^B is defined by (25). Then:

$$\begin{array}{rcl} \dfrac{s_{iat}}{s_{iat}^B} & < & \dfrac{s_{ibt}}{s_{ibt}^B} \qquad (67) \\ \Leftrightarrow & & \dfrac{\left[\frac{\alpha_a\phi_{at}^{\nu}+1-\alpha_a}{\xi[1-\alpha_a]} - 1\right]\widetilde{q}_t\frac{k_{iat}}{\phi_{at}}}{\left[\frac{\alpha_a\left(\phi_{at}^B\right)^{\nu}+1-\alpha_a}{\xi[1-\alpha_a]} - 1\right] q_t \frac{k_{iat}^B}{\phi_{at}^B}} < \dfrac{\left[\frac{\alpha_b\phi_{bt}^{\nu}+1-\alpha_b}{\xi[1-\alpha_b]} - 1\right]\widetilde{q}_t\frac{k_{ibt}}{\phi_{bt}}}{\left[\frac{\alpha_b\left(\phi_{bt}^B\right)^{\nu}+1-\alpha_b}{\xi[1-\alpha_b]} - 1\right] q_t \frac{k_{ibt}^B}{\phi_{bt}^B}} \\ \Leftrightarrow & & \dfrac{\frac{\alpha_a\phi_{at}^{\nu}+1-\alpha_a}{\xi[1-\alpha_a]} - 1}{\frac{\alpha_a\left(\phi_{at}^B\right)^{\nu}+1-\alpha_a}{\xi[1-\alpha_a]} - 1}\dfrac{k_{iat}}{k_{iat}^B}\dfrac{\phi_{at}^B}{\phi_{at}} < \dfrac{\frac{\alpha_b\phi_{bt}^{\nu}+1-\alpha_b}{\xi[1-\alpha_b]} - 1}{\frac{\alpha_b\left(\phi_{bt}^B\right)^{\nu}+1-\alpha_b}{\xi[1-\alpha_b]} - 1}\dfrac{k_{ibt}}{k_{ibt}^B}\dfrac{\phi_{bt}^B}{\phi_{bt}} \\ \Leftrightarrow & & \dfrac{\alpha_a\phi_{at}^{\nu} + [1-\alpha_a][1-\xi]}{\alpha_a\left(\phi_{at}^B\right)^{\nu} + [1-\alpha_a][1-\xi]}\dfrac{k_{iat}}{k_{iat}^B} < \dfrac{\alpha_b\phi_{bt}^{\nu} + [1-\alpha_b][1-\xi]}{\alpha_b\left(\phi_{bt}^B\right)^{\nu} + [1-\alpha_b][1-\xi]}\dfrac{k_{ibt}}{k_{ibt}^B} \end{array}$$

$$\Leftrightarrow \quad \frac{k_{iat}}{k^B_{iat}}\frac{k^B_{ibt}}{k_{ibt}} < \frac{\alpha_b\phi^{\nu}_{bt} + [1-\alpha_b][1-\xi]}{\alpha_b\left(\phi^B_{bt}\right)^{\nu} + [1-\alpha_b][1-\xi]}\frac{\alpha_a\left(\phi^B_{at}\right)^{\nu} + [1-\alpha_a][1-\xi]}{\alpha_a\phi^{\nu}_{at} + [1-\alpha_a][1-\xi]}$$

$$\Leftrightarrow \quad \frac{k_{ia0}}{k^B_{ia0}}\frac{k^B_{ib0}}{k_{ib0}}\prod_{m=1}^{t}\left[\frac{g_{iam}}{g^B_{iam}}\frac{g^B_{ibm}}{g_{ibm}}\right] < \frac{\alpha_b\phi^{\nu}_{bt} + [1-\alpha_b][1-\xi]}{\alpha_a\phi^{\nu}_{at} + [1-\alpha_a][1-\xi]}\frac{\alpha_a\left(\phi^B_{at}\right)^{\nu} + [1-\alpha_a][1-\xi]}{\alpha_b\left(\phi^B_{bt}\right)^{\nu} + [1-\alpha_b][1-\xi]}$$

$$\Leftrightarrow \quad \frac{k_{ia0}}{k^B_{ia0}}\frac{k^B_{ib0}}{k_{ib0}}\prod_{m=1}^{t}\left[\frac{g_{iam}}{g^B_{iam}}\frac{g^B_{ibm}}{g_{ibm}}\right] < \frac{G(\widetilde{q}_t)}{G(q_t)} \tag{68}$$

where one has made use of (33) and where by definition (given (12) and (25)):

$$G(x) = \frac{\alpha_b\left[\frac{1-\alpha_b}{\alpha_b}\frac{\widetilde{p}}{x}\right]^{\frac{\nu}{\nu-1}} + [1-\alpha_b][1-\xi]}{\alpha_a\left[\frac{1-\alpha_a}{\alpha_a}\frac{\widetilde{p}}{x}\right]^{\frac{\nu}{\nu-1}} + [1-\alpha_a][1-\xi]} \tag{69}$$

The LHS of (68) tends to 0 in the long term ($\Leftarrow \frac{g_{iam}}{g^B_{iam}} < \frac{g_{ibm}}{g^B_{ibm}}$, $\forall m$ by Proposition 5).

$\widetilde{q}_t$ and q_t are exogenous functions that can take any values in $\Re^+$. Now $G(x)$ is a strictly positive continuous function in $\Re^+$ that is bounded from above and from below. Indeed $G(+\infty) = \frac{1-\alpha_b}{1-\alpha_a}$ and

$$\lim_{x\to 0} G(x) = \frac{\alpha_b\left[\frac{1-\alpha_b}{\alpha_b}\widetilde{p}\right]^{\frac{\nu}{\nu-1}} + [1-\alpha_b][1-\xi]\,x^{\frac{\nu}{\nu-1}}}{\alpha_a\left[\frac{1-\alpha_a}{\alpha_a}\widetilde{p}\right]^{\frac{\nu}{\nu-1}} + [1-\alpha_a][1-\xi]\,x^{\frac{\nu}{\nu-1}}} = \frac{\alpha_b\left[\frac{1-\alpha_b}{\alpha_b}\right]^{\frac{\nu}{\nu-1}}}{\alpha_a\left[\frac{1-\alpha_a}{\alpha_a}\right]^{\frac{\nu}{\nu-1}}}$$

Therefore the RHS of (68) is also bounded from below and from above. Thus the above inequality (67) must be satisfied after some time[14].

5.7 Proof of Proposition 10

From (50) and (25),

$$\Lambda_{ijt} = \frac{\eta\tau_t}{\left[\frac{\alpha_j\left(\phi^B_{jt}\right)^{\nu}+1-\alpha_j}{\xi[1-\alpha_j]} - 1\right]q_t}\frac{1}{g_{ijt}}\frac{k_{ijt}}{k^B_{ijt}}\left[\frac{\widetilde{q}_t}{\widetilde{q}_{t-1}}\right]^{\frac{1}{1-\nu}}\left[\frac{q_t}{\widetilde{q}_t}\right]^{\frac{1}{1-\nu}}$$

Then :

---

[14] It can easily be checked that inequality (67) holds also when the user costs of capital are sector specific.

$$\begin{aligned}
\Lambda_{iat} &< \Lambda_{ibt}\\
\Leftrightarrow & \frac{\xi\left[1-\alpha_a\right]}{\alpha_a\left(\phi^B_{at}\right)^{\nu}+\left[1-\alpha_a\right]\left[1-\xi\right]}\frac{1}{g_{iat}}\frac{k_{iat}}{k^B_{iat}} < \frac{\xi\left[1-\alpha_b\right]}{\alpha_b\left(\phi^B_{bt}\right)^{\nu}+\left[1-\alpha_b\right]\left[1-\xi\right]}\frac{1}{g_{ibt}}\frac{k_{ibt}}{k^B_{ibt}}\\
\Leftrightarrow & \frac{k_{iat}}{k^B_{iat}}\frac{k^B_{ibt}}{k_{ibt}} < \frac{1-\alpha_b}{1-\alpha_a}\frac{\alpha_a\left(\phi^B_{at}\right)^{\nu}+\left[1-\alpha_a\right]\left[1-\xi\right]}{\alpha_b\left(\phi^B_{bt}\right)^{\nu}+\left[1-\alpha_b\right]\left[1-\xi\right]}\frac{g_{iat}}{g_{ibt}}\\
\Leftrightarrow & \frac{k_{ia0}}{k^B_{ia0}}\frac{k^B_{ib0}}{k_{ib0}}\prod_{m=1}^{t}\left[\frac{g_{iam}}{g^B_{iam}}\frac{g^B_{ibm}}{g_{ibm}}\right] < \frac{1-\alpha_b}{1-\alpha_a}\frac{1}{G(q_t)}\frac{g_{iat}}{g_{ibt}}
\end{aligned}$$

where one has made use of (33) and where $G(x)$ is defined in the proof of Proposition 9 (cfr. (69)).

The LHS tends to 0 in the long term ($\Leftarrow \frac{g_{iam}}{g^B_{iam}} < \frac{g_{ibm}}{g^B_{ibm}}$, $\forall m$ by Proposition 5).

We look at the RHS :
- the first term is a constant;
- the 2d term is bounded by a strictly positive term (see the proof of Proposition 9);
- we now discuss the 3d term. Recall (21), (15) and (22). Then :

$$\frac{g_{iat}}{g_{ibt}} = \frac{\zeta_{at}}{\zeta_{bt}}\frac{\left[2-\theta_{at}\right]}{\left[2-\theta_{bt}\right]}\frac{X_{iat}}{X_{ibt}}$$

The first ratio of the RHS can be developed :

$$\begin{aligned}
\frac{\zeta_{at}}{\zeta_{bt}} &= \frac{\phi_{at}\left[\alpha_a\phi^{\nu}_{at}+1-\alpha_a\right]^{\frac{\xi-\nu}{\nu[1-\xi]}}\left[\left[1-\alpha_a\right]\xi\frac{p_{at}}{\widetilde{q}_t}\right]^{\frac{1}{1-\xi}}}{\phi_{bt}\left[\alpha_b\phi^{\nu}_{bt}+1-\alpha_b\right]^{\frac{\xi-\nu}{\nu[1-\xi]}}\left[\left[1-\alpha_b\right]\xi\frac{p_{bt}}{\widetilde{q}_t}\right]^{\frac{1}{1-\xi}}}\\
&= \left[\frac{1-\alpha_a}{1-\alpha_b}\right]^{\frac{1}{1-\xi}}\frac{\phi_{at}}{\phi_{bt}}\left[\frac{\alpha_a\phi^{\nu}_{at}+1-\alpha_a}{\alpha_b\phi^{\nu}_{bt}+1-\alpha_b}\right]^{\frac{\xi-\nu}{\nu[1-\xi]}}\left[\frac{p_{at}}{p_{bt}}\right]^{\frac{1}{1-\xi}}\\
&= \left[\frac{1-\alpha_a}{1-\alpha_b}\right]^{\frac{1}{1-\xi}}\left[\frac{\frac{1-\alpha_a}{\alpha_a}\widetilde{p}_a}{\frac{1-\alpha_b}{\alpha_b}\widetilde{p}_b}\right]^{\frac{1}{\nu-1}}\left[\frac{1}{H(\widetilde{q}_t)}\right]^{\frac{\xi-\nu}{\nu[1-\xi]}}\left[\frac{p_{at}}{p_{bt}}\right]^{\frac{1}{1-\xi}}
\end{aligned}$$

where one has made use of (12) and where by definition :

$$H(x) = \frac{\alpha_b\phi^{\nu}_{bt}+1-\alpha_b}{\alpha_a\phi^{\nu}_{at}+1-\alpha_a} = \frac{\alpha_b\left[\frac{1-\alpha_b}{\alpha_b}\frac{\widetilde{p}_b}{x}\right]^{\frac{\nu}{\nu-1}}+1-\alpha_b}{\alpha_a\left[\frac{1-\alpha_a}{\alpha_a}\frac{\widetilde{p}_a}{x}\right]^{\frac{\nu}{\nu-1}}+1-\alpha_a}$$

Thus

$$\frac{g_{iat}}{g_{ibt}} = \left[\frac{1-\alpha_a}{1-\alpha_b}\right]^{\frac{1}{1-\xi}} \left[\frac{\frac{1-\alpha_a}{\alpha_a}\widetilde{p}_a}{\frac{1-\alpha_b}{\alpha_b}\widetilde{p}_b}\right]^{\frac{1}{\nu-1}} \left[\frac{1}{H(\widetilde{q}_t)}\right]^{\frac{\xi-\nu}{\nu[1-\xi]}} \frac{2-\theta_{at}}{2-\theta_{bt}}\frac{X_{iat}}{X_{ibt}}\left[\frac{p_{at}}{p_{bt}}\right]^{\frac{1}{1-\xi}}$$

Let us verify how this ratio behaves through time :
- the two first terms are constants;
- $\widetilde{q}_t$ and q_t are exogenous functions that can take any values in $\Re^+$. Now $H(x)$ is a strictly positive continuous function in $\Re^+$ that is bounded from above and from below, and that has the same limits as $G(x)$ defined in the proof of Proposition 9. Thus the third term is bounded from below by a strictly positive term.
- the fourth term is also bounded because the spillovers $\theta_{jt} \in [0,1[\,,\, j = a, b$;
- the fifth term tends to 1 in the long term because $X_{ijt} \to 1$ $(j = a, b)$ asymptotically;
- the sixth term is bounded from below, except if the ratio $\frac{p_{at}}{p_{bt}}$ tends to zero in the long term.

Thus the inequality $\Lambda_{iat} < \Lambda_{ibt}$ will be verified in the long run EXCEPT if the ratio $\frac{p_{at}}{p_{bt}}$ tends to zero in the long term.

5.8 Proof of Proposition 11 (Result (ii))

Given (49), (44) and (45), one obtains :

$$\begin{aligned}
\frac{r_{ijt}}{r^B_{ijt}} &= \frac{s_{ijt}}{s^B_{ijt}} + \Lambda_{ijt} \\
&= \frac{\left[\frac{\alpha_j\phi^{\upsilon}_{jt}+1-\alpha_j}{\xi[1-\alpha_j]} - 1\right]\widetilde{q}_t\frac{k_{ijt}}{\phi_{jt}} + \eta\tau_t\frac{1}{g_{ijt}}\frac{k_{ijt}}{\phi_{jt}}\frac{\phi_{jt}}{\phi_{jt-1}}}{\left[\frac{\alpha_j\left(\phi^B_{jt}\right)^{\nu}+1-\alpha_j}{\xi[1-\alpha_j]} - 1\right] q_t\frac{k^B_{ijt}}{\phi^B_{jt}}} \\
&= \frac{\frac{\alpha_j\phi^{\upsilon}_{jt}+1-\alpha_j}{\xi[1-\alpha_j]} - 1 + \eta\frac{\tau_t}{\widetilde{q}_t}\frac{1}{g_{ijt}}\left[\frac{\widetilde{q}_t}{\widetilde{q}_{t-1}}\right]^{\frac{1}{1-\nu}}}{\frac{\alpha_j\left(\phi^B_{jt}\right)^{\nu}+1-\alpha_j}{\xi[1-\alpha_j]} - 1}\frac{k_{ijt}}{k^B_{ijt}}\frac{\widetilde{q}_t}{q_t}\frac{\phi_{jt}}{\phi^B_{jt}}
\end{aligned}$$

Because the last two ratios do not depend on j, one has

$$\begin{aligned}
\frac{r_{iat}}{r^B_{iat}} &< \frac{r_{ibt}}{r^B_{ibt}} \qquad (70) \\
\Leftrightarrow\ & \frac{\frac{\alpha_a\phi^{\upsilon}_{at}+1-\alpha_a}{\xi[1-\alpha_a]} - 1 + \eta\frac{\tau_t}{\widetilde{q}_t}\frac{1}{g_{iat}}\left[\frac{\widetilde{q}_t}{\widetilde{q}_{t-1}}\right]^{\frac{1}{1-\nu}}}{\frac{\alpha_a\phi^{\upsilon}_{at}+1-\alpha_a}{\xi[1-\alpha_a]} - 1}\frac{k_{iat}}{k^B_{iat}} < \frac{\frac{\alpha_b\phi^{\upsilon}_{bt}+1-\alpha_b}{\xi[1-\alpha_b]} - 1 + \eta\frac{\tau_t}{\widetilde{q}_t}\frac{1}{g_{ibt}}\left[\frac{\widetilde{q}_t}{\widetilde{q}_{t-1}}\right]^{\frac{1}{1-\nu}}}{\frac{\alpha_b\phi^{\upsilon}_{bt}+1-\alpha_b}{\xi[1-\alpha_b]} - 1}\frac{k_{ibt}}{k^B_{ibt}}
\end{aligned}$$

It appears that if the ratio $\frac{\pi_t}{\bar{q}_t}$ is small, the first member of the numerators of each term of the inequality is predominant. Then verifying (70) is close to verify (67), so that Proposition 9 applies.

6 References

Antweiler A., B. Copeland and M. S. Taylor (2001). “Is free trade good for the environment ?”, *The American Economic Review*, 91, 877-908.

Batabyal A. and H. Beladi (Eds.) (2001). *The economics of international trade and the environment*, Lewis Publishers.

Böhringer C. and A. Lange (2005). “On the design of optimal grandfathering schemes for emission allowances”, *European Economic Review*, 49, 2041-2055.

Boucekkine, R., F. del Rio and O. Licandro (2003). “Embodied technological change, learning-by-doing and the productivity slowdown”, *Scandinavian Journal of Economics*, 105, 87-97.

Coe, D. and E. Helpman (1995). “International R&D spillovers”, *European Economic Review*, 39, 859-887.

Copeland B. and M.S. Taylor (2003). *Trade and the environment. Theory and evidence*, Princeton University Press.

Copeland B. and M.S. Taylor (1997). “The trade-induced degradation hypothesis”, *Resource and Energy Economics*, 19(4), 321-344.

den Elzen M. and M. Berk (2004). “Bottom-up approaches for defining future climate mitigation commitments”, RIVM report.

Germain M., Ph. Monfort and Th. Bréchet (2006). “Allocation des efforts de dépollution dans des économies avec spécialisation internationale”, *Revue Economique*, 57(2), 219-239.

Greenwood, J., Z. Hercowitz and P. Krusell (1997). ”Long-run implications of investment-specific technological change”, *American Economic Review*, 87, 342-362.

Ishikawa J. and K. Kiyono (2006). “Greenhouse-gas emission controls in an open economy”, *International Economic Review*, 47(2).

Lee D. M. and A. Batabyal (2002). "Dynamic environmental policy in developing countries with a dual economy", *International Review of Economics & Finance*, 11(2), 191-206.

Malerba, F., M. Mancusi and F. Montobbio (2004). "Innovation and knowledge: Evidence from European data", paper presented at the American Economic Association annual meetings, San Diego 2004.

Rehdanz K. and R. Tol (2004). "On Multi-Period Allocation Of Tradable Emission Permits", CESifo Seminar Series, MIT Press (forthcoming).

Romer, P. (1986). "Increasing return and long-run growth", *Journal of Political Economy*, 94, 1002-1037.

Van Stel, A., and H. Nieuwenhuijsen (2004). "Knowledge spillovers and economic growth: An analysis using data of Dutch Regions in the period 87-95", *Regional Studies*, 38, 393-407.

Environmental Economics & Management Memoranda

113. Thierry BRECHET, Johan EYCKMANS, François GERARD, Philippe MARBAIX, Henry TULKENS, Jean-Pascal van YPERSELE. The impact of the unilateral EU commitment on the stability of international climate agreements. *Climate Policy* 2010.

112. Thierry BRECHET, Sylvette LY. Technological greening, eco-efficiency and no-regret strategy. March 2010.

111. Carlotta BALESTRA, Thierry BRECHET, Stéphane LAMBRECHT. Property rights and biological spillovers: when Hardin meats Meade. February 2010 (also CORE DP 2010/ ?).

110. Thierry BRECHET, Tsvetomir TSACHEV, Vladimir VELIOV. Markets for emission permits with free endowment : a vintage capital analysis. February 2010 (also CORE DP 2010/ ?).

109. Thierry BRECHET, Fabien PRIEUR. Public investment in environmental infrastructures, growth, and the environment. January 2010 (also CORE DP 2010/ ?).

108. Kirill BORISSOV, Thierry BRECHET, Stéphane LAMBRECHT. Median voter environmental maintenance. February 2010 (also CORE DP 2010/ ?).

107. Thierry BRECHET, Carmen CAMACHO, Vladimir VELIOV. Model predictive control, the economy, and the issue of global warming. January 2010 (also CORE DP 2010/ ?).

106. Thierry BRECHET, Tsvetomir TSACHEV and Vladimir M. VELIOV. Prices versus quantities in a vintage capital model. In : *Dynamic Systems, Economic Growth, and the Environment*, Jesus Crespo Cuaresma, Tapio Palokangas, Alexander Tarasyev (eds), Dynamic Modeling and Econometrics in Economics and Finance 12, 141-159, 2010.

105. Thierry BRECHET, Pierre-André JOUVET. Why environmental management may yield no-regret pollution abatement options. *Ecological Economics*, 68, 1770-1777, 2009.

104. Thierry BRECHET et Henry TULKENS. Mieux répartir les coûts de la politique climatique. *La vie des idées.fr*, 2009.

103. Thierry BRECHET. Croissance économique, environnement et bien-être. In : Alain Ayong Le Kama, Pour une croissance verte … et sociale, *La lettre de l'AFSE*, 74:9-13, 2009.

102. Henry TULKENS. Stabilité de l'accord et règles d'allocation initiale des droits d'émission. Commentaire sur le Rapport de Jean Tirole "Politique climatique : une nouvelle architecture internationale", 9 octobre 2009.

101. Giorgia OGGIONI, Yves SMEERS. Evaluatinq the impact of average cost based contracts on the industrial sector in the European emission trading scheme. *CEJOR* 17:181-217, 2009.

100. Raouf BOUCEKKINE, Marc GERMAIN. The burden sharing of polllution abattement costs in multi-regional open economics. *The B.E. Journal of Macroeconomics*, 9 (1 Topics), 2009.

99. Rabah AMIR, Marc GERMAIN, Vincent VAN STEENBERGHE. On the impact of innovation on the marginal abatement cost curve. *Journal of Public Economic Theory*, 10(6):985-1010, 2008.

98. Maria Eugenia SANIN, Skerdilajda ZANAJ. Clean technology adoption and its influence on tradeable emission permit prices. April 2009 (also CORE DP 2009/29).

97. Jerzy A. FILAR, Jacek B. KRAWCZYK, Manju AGRAWAL. On production and abatement time scales in sustainable development. Can we loose the *sustainability screw* ? April 2009 (also CORE DP 2009/28).

96. Giorgia OGGIONI, Yves SMEERS. Evaluating the impact of average cost based contracts on the industrial sector in the European emission trading scheme. *CEJOR* (2009) 17: 181-217.

95. Marc GERMAIN, Henry TULKENS, Alphonse MAGNUS. Dynamic core-theoretic cooperation in a two-dimensional international environmental model, April 2009 (also CORE DP 2009/21).

94. Henry TULKENS, Vincent VAN STEENBERGHE. "Mitigation, Adaptation, Suffering" : In search of the right mix in the face of climate change, June 2009.

93. Luisito BERTINELLI, Eric STROBL. The environmental Kuznets curve semi-parametrically revisited. *Economics Letters,* 88 (2005) 350-357.

92. Maria Eugenia SANIN, Francesco VIOLANTE. Understanding volatility dynamics in the EU-ETS market: lessons from the future, March 2009 (also CORE DP 2009/24).

91. Thierry BRECHET, Henry TULKENS. Beyond BAT : Selecting optimal combinations of available techniques, with an example from the limestone industry. *Journal of Environmental Management*, 90:1790-1801, 2009.

90. Giorgia OGGIONI, Yves SMEERS. Equilibrium models for the carbon leakage problem. December 2008 (also CORE DP 2008/76).

89. Giorgia OGGIONI, Yves SMEERS. Average power contracts can mitigate carbon leakage. December 2008 (also CORE DP 2008/62).

88. Thierry BRECHET, Johan EYCKMANS, François GERARD, Philippe MARBAIX, Henry TULKENS, Jean-Pascal van YPERSELE. The impact of the unilateral EU commitment on the stability of international climate agreements. (also CORE DP 2008/61).

87. Raouf BOUCEKKINE, Jacek B. KRAWCZYK, Thomas VALLEE. Towards an understanding of tradeoffs between regional wealth, tightness of a common environmental constraint and the sharing rules. (also CORE DP 2008/55).

86. Thierry BRECHET, Tsvetomir TSACHEV, Vladimir VELIOV. Prices versus quantities in a vintage capital model. March 2009 (also CORE DP 2009/15).

85. David DE LA CROIX, Davide DOTTORI. Easter Island's collapse : a tale of a population race. *Journal of Economic Growth*, 13:27-55, 2008.

84. Thierry BRECHET, Stéphane LAMBRECHT, Fabien PRIEUR. Intertemporal transfers of emission quotas in climate policies. *Economic Modelling*, 26(1):126-143, 2009.

83. Thierry BRECHET, Stéphane LAMBRECHT. Family altruism with renewable resource and population growth. *Mathematical Population Studies*, 16:60-78, 2009.

82. Thierry BRECHET, Alexis GERARD, Giordano MION. Une évaluation objective des nuisances subjectives de l'aéroport de Bruxelles-National. *Regards Economiques*, 66, Février 2009.

81. Thierry BRECHET, Johan EYCKMANS. Coalition theory and integrated assessment modeling : Lessons for climate governance. In E. Brousseau, P.A. Jouvet and T. Tom Dedeurwaerder (eds). Governing Global Environmental Commons: Institutions, Markets, Social Preferences and Political Games, Oxford University Press, 2009.

80. Parkash CHANDER and Henry TULKENS. Cooperation, stability, and self-enforcement in international environmental agreements : A conceptual discussion. In R. Guesnerie and H. Tulkens (eds). *The Design of Climate Policy*, CESifo Seminar Series, The MIT Press, 2008.

79. Mirabelle MUULS. The effect of investment on bargaining positions. Over-investment in the case of international agreements on climate change. September 2008

78. Pierre-André JOUVET, Philippe MICHEL, Pierre PESTIEAU. Public and private environmental spending : a political economy approach. *Environmental Economics and Policy Studies*, 9(3):177-191, 2008.

77. Fabien PRIEUR. The environmental Kuznets curve in a world of irreversibility. *Economic Theory*, 40(1) : 57-90, 2009.

76. Raouf BOUCEKKINE, Natali HRITONENKO and Yuri YATSENKO. Optimal firm behavior under environmental constraints. April 2008. (also CORE DP 2008/24).

75. Giorgia OGGIONI and Yves SMEERS. Evaluating the impact of average cost based contracts on the industrial sector in the European emission trading scheme. January 2008 (also CORE DP 2008/1).

74. Thierry BRECHET and Pierre-André JOUVET. Environmental innovation and the cost of pollution abatement revisited. *Ecological Economics*, 65:262-265, 2008.

73. Ingmar SCHUMACHER and Benteng ZOU. Pollution perception : A challenge for intergenerational equity. *Journal of Environmental Economics and Management*, 55, 296-309, 2008.

72. Thierry BRECHET et Patrick VAN BRUSSELEN. Le pic pétrolier: un regard d'économiste. *Reflets et Perspectives de la vie économique*, Tome XLVI, n° 4, 63-81, 2007.

71. Thierry BRECHET. L'énergie : mutations passées et mutations en cours. *Reflets et Perspectives de la vie économique*, Tome XLVI, n° 4, 5-11, 2007.

70. Marc GERMAIN, Alphonse MAGNUS and Vincent VAN STEENBERGHE. How to design and use the clean development mechanism under the Kyoto Protocol? A developing country perspective. *Environmental & Resource Economics*, 38(1):13-30, 2007.

69. Thierry BRECHET en Pierre PICARD. Economische instrumenten voor de regulering van de geluidshinder in de omgeving van luchthavens? *Brussels Studies*, nummer 12, 3 december 2007.

68. Thierry BRECHET et Pierre PICARD. Des instruments économiques pour la régulation des nuisances sonores autour des aéroports? *Brussels Studies*, numéro 12, 3 décembre 2007, www.brusselsstudies.be.

67. Thierry BRECHET and Pierre PICARD. Can economic instruments regulate noise pollution in locations near airports? *Brussels Studies*, issue 12, 2007 December the 3rd , www.brusselsstudies.be.

66. Pierre-André JOUVET, Pierre PESTIEAU and Gregory PONTHIERE. Longevity and Environmental quality in an OLG model. September 2007 (also available as CORE DP 2007/69).

65. Raouf BOUCEKKINE and Marc GERMAIN. Impacts of emission eduction policies in a multi-regional multi-sectoral small open economy with endogenous growth. February 2007 (also available CORE DP 2007/11).

64. Parkash CHANDER and Subhashini MUTHUKRISHNAN. Green consumerism and collective action. June 2007 (also available as CORE DP 2007/58).

63. Jakub GROWIEC and Ingmar SCHUMACHER. Technological opportunity, long-run growth and convergence. July 2007 (also available as CORE DP 2007/57).

62. Maria Eugenia SANIN and Skerdilajda ZANAJ. Environmental innovation under Cournot competition. June 2007. (also available as CORE DP 2007/50)

61. Thierry BRECHET and Stéphane LAMBRECHT. Family altruism with a renewable resource and population growth. October 2006 (also available as CORE DP 2006/35).

60. Thierry BRECHET, François GERARD and Henry TULKENS. Climate Coalitions: a theoretical and computational appraisal. February 2007 (also available as CORE DP 2007/3).

59. Thierry BRECHET. L'environnement dans tous ses états. *Regards Economiques*, n° 50, 26-32, Avril 2007.

58. Thierry BRECHET and Susana PERALTA. The race for polluting permitsThierry. March 2007 (also available as CORE DP 2007/27).

57. Giorgia OGGIONI, Ina RUMIANTSEVA and Yves SMEERS. Introduction of CO_2 emission certificates in a simplified model of the Benelux electricity network with small and industrial consumers. Reprint from *Proceedings of the International Conference on Clean Electrical Power*, Capri, Italy, May 21-23, 2007.

56. Agustin PEREZ-BARAHONA. The problem of non-renewable energy resource in the production of physical capital. January 2007 (also available as CORE DP 2007/8).

55. Thierry BRECHET, Benoît LUSSIS. The contribution of the clean development mechanism to national climate policies. *Journal of Policy Modelling*, 28(9), 981-994, December 2006.

54. Ingmar SCHUMACHER. Endogenous discounting via wealth, twin-peaks and the role of technology. November 2006 (also available as CORE DP 2006/104).

53. Ingmar SCHUMACHER. On optimality, endogenous discounting and wealth accumulation. October 2006 (also available as CORE DP 2006/103).

52. Jakub GROWIEC, Ingmar SCHUMACHER. On technical change in the elasticities of resource inputs. November 2006. (also available as CORE DP 2006/63).

51. Maria Eugenia SANIN. Market Design in Wholesale Electricity Markets. October 2006 (also available as CORE DP 2006/100).

50. Luisito BERTINELLI, Eric STROBL and Benteng ZOU. Polluting technologies and sustainable economic development. June 2006 (also available as CORE DP 2006/52).

49. Marc GERMAIN, Alphonse MAGNUS. Prices versus quantities: Stock pollution control with repeated choice of the instrument. October 2005. *Journal of Computational and Applied Mathematics*, 197 (2006) 437-445.

48. Agustin PEREZ-BARAHONA. Capital accumulation and exhaustible energy resources: a special functions case. September 2006 (also available as CORE DP 2007/9).

47. Philippe TULKENS, Henry TULKENS. The White House and the Kyoto Protocol: Double standards on uncertainties and their consequences. May 2006 (also TERI School of Advanced Studies WP Series #1).

46. Thierry BRECHET, Pierre-André JOUVET. Environmental innovation and the cost of pollution abatement. January 2006 (also available as CORE DP 2006/40).

45. Fabien PRIEUR. The implication of irreversible pollution on the relation between growth and the environment: The degenerate Kuznets curve. February 2006.

44. Thierry BRECHET, Marc GERMAIN, Philippe MONTFORT. Allocation des efforts de dépollution dans des économies avec spécialisation internationale. *Revue Economique*, 57(2), Mars 2006.

43. Ingmar SCHUMACHER and Benteng ZOU. Habit in Pollution, A Challenge for Intergenerational Equity. March 2006 (also available as CORE DP 2006/6).

42. Jean-Charles HOURCADE, P.R. SHUKLA and Sandrine MATHY. Cutting the Climate-Development Gordian Knot – Economic options in a politically constrained world. September 2005.

41. Urs LUTERBACHER. Climate Change, the Kyoto Protocol, and Transatlantic Relations. November 2005.

40. Parkash CHANDER and Henry TULKENS. Cooperation, Stability and Self-Enforcement in International Environmental Agreements: A Conceptual Discussion. July 2005.

39. Paul-Marie BOULANGER et Thierry BRECHET. Le Mécanisme pour un Développement Propre tiendra-t-il ses promesses ? *Reflets et Perspectives de la Vie Economique*, Tome XLIV – 2005 – N° 3, 5-27.

38. Paul-Marie BOULANGER and Thierry BRECHET. Models for policy-making in sustainable development: The state of the art and perspectives for research. *Ecological Economics*, 55, 337-350, 2005.

37. Johan EYCKMANS an Henry TULKENS. Optimal and Stable International Climate Agreements. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

36. Thierry BRECHET and Benoît LUSSIS. The Clean Development Mechanism in Belgian Climate Policy. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

35. Vincent VAN STEENBERGHE. The impact of banking on permits prices and compliance costs. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

34. Johan EYCKMANS, Denise VAN REGEMORTER and Vincent VAN STEENBERGHE. Kyoto-permit prices and compliance costs: an analysis with MacGEM. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

33. Johan EYCKMANS, Bert WILLEMS and Jean-Pascal VAN YPERSELE. Climate Change: Challenges for the World. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

32. Marc GERMAIN, Stef PROOST and Bert SAVEYN. The Belgian Burden Sharing. October 2005. Reprint from "*Economic Aspects of Climate Change Policy : A European and Belgian Perspective*", a joint product of CES-K.U.Leuven and CORE-UCL, edited by Bert Willems, Johan Eyckmans and Stef Proost, published by ACCO, 3000 Leuven (Belgium)

31. Ingmar SCHUMACHER. Reviewing Social Discounting within Intergenerational Moral Intuition. June 2005.

30. Stéphane LAMBRECHT. The effects of a demographic shock in an OLG economy with pay-as-you-go pensions and property rights on the environment: the case of selfish households. January 2005.

29. Stéphane LAMBRECHT. Maintaining environmental quality for overlapping generations: Some Reflections on the US Sky Trust Initiative. May 2005.

28. Thierry BRECHET, Benoît LUSSIS. The contribution of the Clean Development Mechanism to national climate policies. April 2005.

27. Thierry BRECHET, Stéphane LAMBRECHT, Fabien PRIEUR. Intergenerational transfers of pollution rights and growth. May 2005 (also availabe as CORE DP 2005/42).

26. Maryse LABRIET, Richard LOULOU. From non-cooperative CO_2 abatement strategies to the optimal world cooperation: Results from the integrated MARKAL model. April 2005.

25. Marc GERMAIN, Vincent VAN STEENBERGHE, Alphonse MAGNUS. Optimal Policy with Tradable and Bankable Pollution Permits : Taking the Market Microstructure into Account.*Journal of Public Economy Theory*, 6(5), 2004, 737-757.

24. Marc GERMAIN, Stefano LOVO, Vincent VAN STEENBEGHE. De l'impact de la microstructure d'un marché de permis de polluer sur la politique environnementale. *Annales d'Economie et de Statistique*, n° 74 – 2004, 177-208.

23. Marc GERMAIN, Alphonse MAGNUS, Vincent VAN STEENBERGHE. Should developing countries participate in the Clean Development Mechanism under the Kyoto Protocol ? The low-hanging fruits and baseline issues. December 2004.

22. Thierry BRECHET et Paul-Marie BOULANGER. Le Mécanisme pour un Développement Propre, ou comment faire d'une pierre deux coups. *Regards Economiques*, Ires n° 27, janvier 2005.

21. Sergio CURRARINI & Henry TULKENS. Stable international agreements on transfrontier pollution with ratification constraints. In C. Carraro and V. Fragnelli (eds.), *Game Practice and the Environment*. Cheltenham, Edward Elgar Publishing, 2004, 9-36. (also available as CORE Reprint 1715).

20. Agustin PEREZ-BARAHONA & Benteng ZOU. A comparative study of energy saving technical progress in a vintage capital model. December 2004.

19. Agustin PEREZ-BARAHONA & Benteng ZOU. Energy saving technological progress in a vintage capital model. December 2004.

18. Matthieu GLACHANT. Voluntary agreements under endogenous legislative threats and imperfect enforcement. November 2004.

17. Thierry BRECHET, Stéphane LAMBRECHT. Puzzling over sustainability: an equilibrium analysis. November 2004.

16. Vincent VAN STEENBERGHE. Core-stable and equitable allocations of greenhouse gas emission permits. October 2004. (also available as CORE DP 2004/75).

15. Pierre-André JOUVET Philippe MICHEL, Pierre PESTIEAU. Public and private environmental spending. A political economy approach. September 2004. (also available as CORE DP 2004/68).

14. Thierry BRECHET, Marc GERMAIN, Vincent VAN STEENBERGHE. The clean development mechanism under the Kyoto protocol and the 'low-hanging fruits' issue. July 2004. (also available as CORE DP 2004/81).

13. Thierry BRECHET, Philippe MICHEL. Environmental performance and equilibrium. July 2004. (also available as CORE DP 2004/72).

12. Luisito BERTINELLI, Eric STROBL. The Environmental Kuznets Curve semi-parametrically revisited. July 2004. (also available as CORE DP 2004/51).

11. Axel GOSSERIES, Vincent VAN STEENBERGHE. Pourquoi des marchés de permis de polluer ? Les enjeux économiques et éthiques de Kyoto. April 2004. (also available as IRES discussion paper n° 2004-21).

10. Vincent VAN STEENBERGHE. CO_2 Abatement costs and permits price : Exploring the impact of banking and the role of future commitments. December 2003. (also available as CORE DP 2003/98).

9. Katheline SCHUBERT. Eléments sur l'actualisation et l'environnement. March 2004.

8. Marc GERMAIN. Modélisations de marchés de permis de pollution. July 2003.

7. Marc GERMAIN. Le Mécanisme de Développement Propre : Impacts du principe d'additionalité et du choix de la baseline. January 2003.

6. Thierry BRECHET et Marc GERMAIN. Les affres de la modélisation. May 2002.

5. Marc GERMAIN and Vincent VAN STEENBERGHE. Constraining equitable allocations of tradable CO_2 emission quotas by acceptability, *Environmental and Resource Economics*, (26) 3, 2003.

4. Marc GERMAIN, Philippe TOINT, Henry TULKENS and Aart DE ZEEUW. Transfers to sustain dynamic core-theoretic cooperation in international stock pollutant control, *Journal of Economic Dynamics & Control*, (28) 1, 2003.

3. Thierry BRECHET, Marc GERMAIN et Philippe MONTFORT. Spécialisation internationale et partage de la charge en matière de réduction de la pollution. (also available as IRES discussion paper n°2003-19).

2. Olivier GODARD. Le risque climatique planétaire et la question de l'équité internationale dans l'attribution de quotas d'émission échangeable. May 2003.

1. Thierry BRECHET. Entreprise et environnement : des défis complémentaires ? March 2002. Revue Louvain.

Environmental Economics & Management Memorandum

Chair Lhoist Berghmans in Environmental Economics and Management
Center for Operations Research & Econometrics (CORE)
Université catholique de Louvain (UCL)
Voie du Roman Pays 34
B-1348 Louvain-la-Neuve, Belgium