International coordination over emissions and R&D expenditures: What does oil scarcity change?

Belgodere, Antoine and Prunetti, Dominique
UMR CNRS LISA 6240

2007

International coordination over emissions and R&D expenditures: What does oil scarcity change? (Preliminary Draft please don't quote)

Antoine Belgodere*
Dominique Prunetti†

CREShS
Université de Corse - Campus Caraman - 7, avenue Jean Nicoli
20250 CORTE
FRANCE

June 2007

1 Introduction

In a recent report (IEA (2006)), the International Energy Agency emphasises altogether the historically high increase in oil prices and in CO2 concentration. Both of them increased of more than 20 percent during the last decade. The report concludes in favour of policies aiming at promoting energy savings along with the use of low-carbon technology. Those policies should rely on the R&D budgets, in order to achieve technological progress in areas like hydrogen and fuel cells, advanced renewable energies, next-generation biofuels and energy storage.

The interaction between Climate policy and endogenous technological change has been recently studied in several papers (see Golombek and Hoel (2005) and Golombek and Hoel (2006) for overviews). However, none of them

*belgodere@univ-corse.fr
†prunetti@univ-corse.fr

focused on the interaction between the oil price, technological progress and Greenhouse gas emissions.

This paper adds to this literature by studying an international negotiation process about global warming which involves three state variables: the pollution, the marginal extraction cost of the resource and the level of knowledge in the renewable non polluting resource sector. Our approach uses differential game models closed to van der Ploeg and de Zeeuw (1994) who compare centralized and decentralized solutions in a global pollution problem with investment in clean technology[1]. In our paper, as in van der Ploeg and de Zeeuw (1994), we compare the equilibrium outcome under international coordination of environmental policies with equilibrium outcome that arises when players adopt "open-loop" strategies in a N-symmetric players game [2]. In computing the decentralized equilibrium, we rely on the simplifying assumption that taxation is an appropriate instrument of environmental policy, as opposed to other instruments such as standards or marketable permits. This assumption allows us to abstract from complex issues of what determine the choice of policy instruments. Finally, a last feature of our model is that we consider two asymmetrical players, as in List and Mason (2001), which can be thought of as two groups of nations: the rich ones and the poor ones. We indeed think that the asymmetry assumption is more realistic than the symmetry one as far as climate change problems are concerned.

The rest of the paper is organized as follows. In Section 2, we develop the general structure of the model. In Section 3, we derive the cooperative and non-cooperative equilibria. In Section 4, we implement a Monte Carlo procedure enabling to numerically solve the model. Results are presented in Section 5 while Section 6 concludes.

2 The model

We consider a world with 2 players; indexed by $i = 1, 2$; corresponding to two asymmetric countries which differ both in terms of their wealth and of their sensitiveness to the environment. Both countries use oil, i.e. a non renewable polluting energy, to produce an homogeneous consumption good.

[1] This former paper did not link those issues to the problem of oil depletion as it is done here.

[2] In the differential games literature, it is well known that "open-loop" give smaller payoffs than "closed-loop" strategies. The principal reason is that "closed-loop" strategies, like linear Markov perfect strategies, ensure subgame perfection contrary to open-loop strategies (Cf., e.g., Fudenberg and Tirole (1992), p.74-77).

2.1 Scarcity and pollution

Oil extraction has two harmful effects.

First, it lowers the oil stock for the future. In this paper, we don't model oil as a finite-size non-renewable stock. We rather assume that the oil stock is infinite, but that the marginal extraction cost is an increasing function of the cumulated extractions. Moreover, the marginal extraction cost does not depend on the instantaneous rate of extraction (in other words, the extraction cost is a linear function of the rate of extraction). It follows that the resource price, P, equates its marginal cost expressed in term of the aggregate output[3]. We have:

$$\dot{P} = \sum_{i=1}^{2} \zeta E_i \tag{1}$$

Where E_i is the rate of resource extraction by country i, and ζ is a parameter. ζ denotes the *importance* of scarcity. Indeed, for $\zeta = 0$, the resource is infinitely available at a constant marginal cost. On the other hand, for $\zeta \to \infty$, the marginal cost of extraction increases so fast that the extraction is not profitable anymore.

The second harmful effect of oil extraction is pollution. In this paper, we model oil pollution as a cumulative process. The stock of pollution follows:

$$\dot{M} = \sum_{i=1}^{2} E_i - \delta M \tag{2}$$

where δ is a constant rate of decay of pollution.

Under this specification, pollution generates an external cost given by $\alpha_i M^2$, where $\alpha_i > 0$ measures the degree of sensitivity to pollution of country i.

2.2 The resource sector

The resource is used as an input to produce an aggregate good Q_i, together with a renewable non polluting energy. *Ceteris Paribus*, an improvement of the knowledge about the backstop technology makes profitable a shift from hydrocarbon to clean energy in a number of economic activities. Thus, for a given E_i, this improvement generates an increase in the opportunity cost of E_i. This effect is represented in figure 1[4].

[3]For simplicity stake, we also assume no rent due to imperfect competition on the oil market.

[4]Technological changes are presented, for illustrative purpose, at a point of time to be able to represented the effects in a two-dimensional figure. In a dynamic framework, the effects of changes are, in fact, integrated over time.

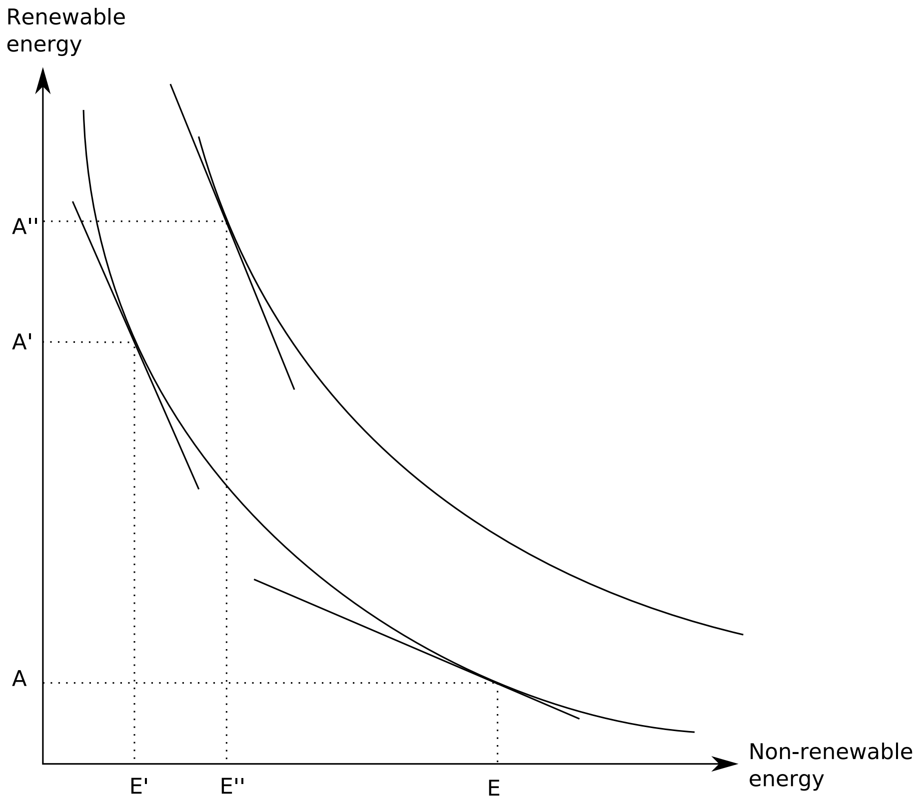

Figure 1: substitution between oil and clean energy

Let A be a renewable non polluting resource and X a coefficient denoting the level of knowledge in the renewable energy sector. For a given X, the optimal level of production is Q, and the optimal combination of oil and clean energy is given by (E, A). Now, what happens if X increases, inducing a fall in the cost of the clean energy? First, the relative price of clean energy to oil falls. Would this change in the price ratio have not affected the quantity of output produced, the new optimal combination of input would have been (E', A'), with more clean energy and less oil compared to the previous equilibrium. But as the fall in the clean energy price also induces a fall in the aggregate energy price, this creates incentives to produce a greater level of final output. Let the new optimal output level be given by Q'. In this situation, the new optimal combination of input is (E'', A''), with both more clean energy and more oil compared to (E', A'). Actually, whether E'' is greater or smaller than E is not an unambiguous issue. It depends both on the elasticity of the production with respect to the energy price and on the elasticity of substitution between oil and clean energy. Here, however, we assume that different energy sources are strong enough substitutes to ensure that a fall in the clean energy price always result in a fall in the oil consumption [5].

Within this setting, the two consequences of an increase in X are, first, an increase in the production, and second, a fall in the use of oil. The net production function of country i can then be written as[6]:

$$Q_i = (\beta_{i,1} - X)\, E_i - \beta_2 E_i^2 + \eta_{i,1} X - \eta_2 X^2$$

where $(\beta_{i,1}, \beta_2, \eta_{i,1}, \eta_2) > 0$ are parameters[7].

Figure 2 displays the production function net of the oil cost.

The lower curve represents the net production as a function of the oil use before any increase in the knowledge stock. As soon as X increases, the net production switches to the second upper curve. As expected, the new level of production is higher while the new level of oil is lower.

2.3 The research sector

Economic activities in the research sector results in an increase in X. As X is a pure public good, the motives to invest in research are twofold: first, R&D

[5] Joules that come from oil are perfect substitute of joules that come from any other energy source. Only storage and transportation differ from one source to another.

[6] An alternative way to model those effects could consist in introducing the clean energy A as a control variable into the model. Our current formulation is simpler but it has the drawback that Inada conditions may not hold. For Monte Carlo procedure of section 4, parameters are chosen such that the non negativity condition over E_i is warranted for any relevant future.

[7] The interpretation of this parameters is explain below, see 2.4.

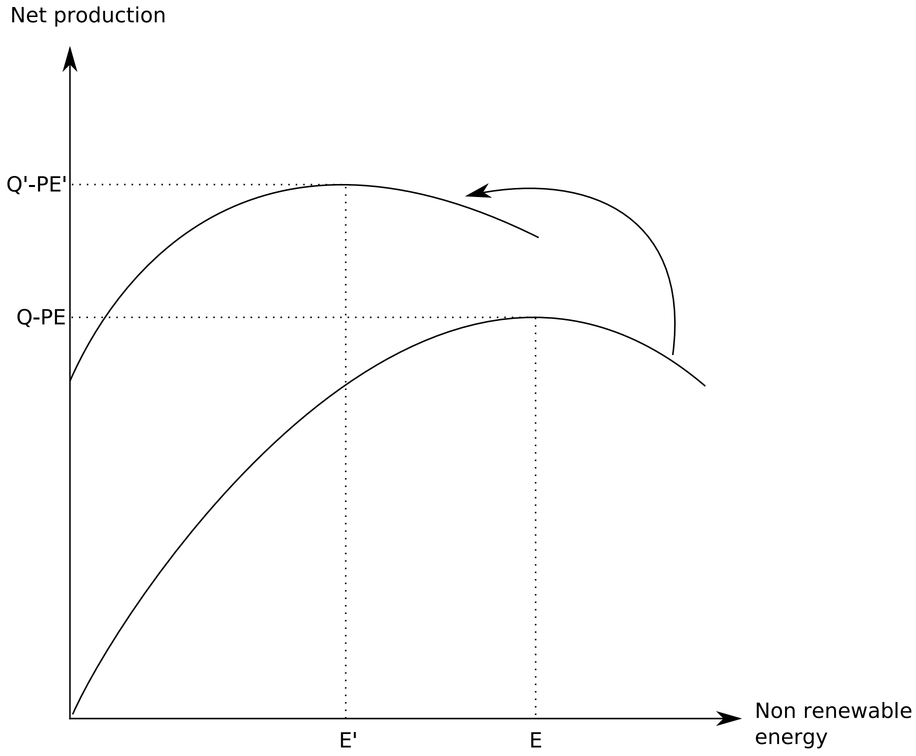

Figure 2: Impact of a technology improvement in the renewable energy sector

investment enables to lower the economic impact of the increasing scarcity of the nonrenewable resource; second, R&D investment lowers the abatement cost of an environmental policy that aims at substituting non-polluting to polluting ones. As far as country i invests I_i in research, X follows:

$$\dot{X} = \sigma \left(I_1 + I_2 \right) - \epsilon X \tag{3}$$

where σ and ϵ are positive parameters.

This knowledge production function displays two main features. First, with no investment in research, X decreases by ϵX per unit of time. This feature accounts for the necessity to maintain some minimum level of research activity to transmit the knowledge from old generations to new generations. Second, the productivity in research is constant. In consequence, the growth of the knowledge stock will not be sustainable in the long-run[8].

Finally, it is assumed that each country faces an investment cost given by γI_i^2, where γ is a constant parameter.

2.4 Welfare functions

The welfare function of country i is given by:

$$W_i = \int_0^\infty e^{-\rho t} \left[\left(\beta_{i,1} - P - X \right) E_i - \beta_2 E_i^2 + \eta_{i,1} X - \eta_2 X^2 - \alpha_i M^2 - \gamma I_i^2 \right] dt$$

where ρ is the discount rate.

Both countries differ from one each other with respect to their sensitiveness to the environment and to their wealth. The higher α_i, the higher the sensitiveness to the environment of country i. The higher are $\beta_{i,1}$ and $\eta_{i,1}$, the richer is country i. Indeed, the wealth of a country comes from its capital

[8] This assumption differs from the one usually made in the endogenous growth literature, such as in Romer (1990), where the research productivity is linear with respect to the knowledge stock. However, it should be noted that modelling the evolution of an aggregate stock of knowledge is not the same as modelling the evolution of a sectoral stock of knowledge. As pointed out by Aghion and Howitt (1998), the number of new ideas that remain undiscovered in one particular sector should not be thought of as an infinite stock. The linear modelling in macroeconomic models accounts both for the knowledge increase in each sector (quality innovations) and for the increase of the number of sectors (variety innovations). Within a given sector, the best way to model the innovation would probably be a logistic function. It would account for the giants' shoulders effect when the stock of knowledge is low, and then for the rarefaction of the remaining undiscovered ideas when the stock of knowledge is high. To keep in touch with the linear quadratic formulation, the simplest specification is the constant productivity assumption made in equation 3

accumulation. The capital accumulation makes the energy (both clean and polluting energy) more productive.

Countries are supposed to be asymmetric. Let Country 1 be the rich one. We pose:

$$\beta_{1,1} > \beta_{2,1}$$

and

$$\eta_{1,1} > \eta_{2,1}$$

Should we also assume that country 1 is the more sensitive to the environment? Following the Environmental Kuznets Curve which involves an inverted U relationship between environmental pressure and per capita income, such an assumption would appear reasonable.

However, as pointed out by the recent IPCC report (IPCC (2007)), global warming is going to harm more severely developing countries than rich ones. Consequently, it is not obvious whether α_1 should be superior or inferior to α_2.

We then choose to investigate the two polar cases: In the first one, the rich country is supposed to be more sensitive to the environmental damage than the poor country ($\alpha_1 > \alpha_2$); In the second case, the opposite holds ($\alpha_1 < \alpha_2$). The simulations in section (see 5) are run under both those alternative specifications.

3 Cooperative and non-cooperative equilibria

3.1 Cooperative equilibrium

In this section, we characterize the optimal path which allows to maximize the sum W of both national objectives.

$$W \equiv W_1 + W_2$$

subject to 1, 2 and 3. This path characterizes the shape of an international agreement between both countries.

The cooperative problem can be restated as the minimization of

$$W = \int_0^\infty (y' Q^c y + v' R^c v) \, dt$$

subject to

$$\dot{y} = Ay + B^c v$$

with

$$y(t) \equiv e^{-\frac{1}{2}\rho t} \begin{pmatrix} P \\ M \\ X \\ 1 \end{pmatrix} ; \; v(t) \equiv e^{-\frac{1}{2}\rho t} \begin{pmatrix} \frac{X}{2\sqrt{\beta_2}} - \frac{\beta_{1,1}}{2\sqrt{\beta_2}} + \frac{P}{2\sqrt{\beta_2}} + \sqrt{\beta_2} E_1 \\ \frac{X}{2\sqrt{\beta_2}} - \frac{\beta_{2,1}}{2\sqrt{\beta_2}} + \frac{P}{2\sqrt{\beta_2}} + \sqrt{\beta_2} E_2 \\ I_1 \\ I_2 \end{pmatrix}$$

$$A \equiv \begin{pmatrix} -\frac{\rho}{2} - \frac{\zeta}{\beta_2} & 0 & -\frac{\zeta}{\beta_2} & \frac{\beta_{1,1}\,\zeta + \beta_{2,1}\,\zeta}{2\beta_2} \\ -\frac{1}{\beta_2} & -\frac{\rho}{2} - \delta & -\frac{1}{\beta_2} & \frac{\beta_{1,1} + \beta_{2,1}}{2\beta_2} \\ 0 & 0 & \frac{-\rho}{2} - \epsilon & 0 \\ 0 & 0 & 0 & -\frac{\rho}{2} \end{pmatrix}$$

$$B^c \equiv \begin{pmatrix} \frac{\zeta}{\sqrt{\beta_2}} & \frac{\zeta}{\sqrt{\beta_2}} & 0 & 0 \\ \frac{1}{\sqrt{\beta_2}} & \frac{1}{\sqrt{\beta_2}} & 0 & 0 \\ 0 & 0 & \sigma & \sigma \\ 0 & 0 & 0 & 0 \end{pmatrix} ; \; R^c \equiv \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \gamma & 0 \\ 0 & 0 & 0 & \gamma \end{pmatrix}$$

$$Q^c \equiv \begin{pmatrix} -\frac{1}{2\beta_2} & 0 & -\frac{1}{2\beta_2} & \frac{\beta_{1,1}}{4\beta_2} + \frac{\beta_{2,1}}{4\beta_2} \\ 0 & \alpha_1 + \alpha_2 & 0 & 0 \\ -\frac{1}{2\beta_2} & 0 & -\frac{1}{2\beta_2} + 2\eta_2 & \frac{\beta_{1,1} + \beta_{2,1}}{4\beta_2} - \frac{1}{\eta_2} \\ \frac{\beta_{1,1}}{4\beta_2} + \frac{\beta_{2,1}}{4\beta_2} & 0 & \frac{\beta_{1,1} + \beta_{2,1}}{4\beta_2} - \frac{1}{\eta_2} & -\frac{\beta_{1,1}^2}{4\beta_2} - \frac{\beta_{2,1}^2}{4\beta_2} \end{pmatrix}$$

$$S^c \equiv B^c R^{c\,-1} B^{c'}$$

The optimal linear strategy is given by

$$v^c = C^c y$$

where $C^c = -R^{c\,-1} B^{c'} K^c$ and K^c is the symmetric stabilizing solution of the following algebraic Riccati equation:

$$A' K^c + K^c A - K^c S^c K^c + Q^c = 0$$

One of the purposes of this paper is to analyze the equilibrium strategies of the players. However, C^c cannot be analyzed by itself because of the matrix transformations required to solve the model. We have to define the following two transformation matrices:

$$TR_1 = \begin{pmatrix} \frac{0.5}{\sqrt{\beta_2}} & 0 & \frac{0.5}{\sqrt{\beta_2}} & -\frac{0.5\beta_{1,1}}{\sqrt{\beta_2}} \\ \frac{0.5}{\sqrt{\beta_{2,2}}} & 0 & \frac{0.5}{\sqrt{\beta_{2,2}}} & -\frac{0.5\beta_{2,1}}{\sqrt{\beta_2}} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}; TR_2 = \begin{pmatrix} \frac{0.5}{\sqrt{\beta_2}} & 0 & 0 & 0 \\ 0 & \frac{0.5}{\sqrt{\beta_2}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

which enable us to compute the following matrix Z^c:

$$Z^c = TR_2 \left(C^c - TR_1\right) = \begin{pmatrix} z^c_{1,1} & \cdots & \cdots & z^c_{1,4} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ z^c_{4,1} & \cdots & \cdots & z^c_{4,4} \end{pmatrix}$$

The optimal strategies for each of our two players are then given by:

$$\begin{pmatrix} E^c_1 \\ E^c_2 \\ I^c_1 \\ I^c_2 \end{pmatrix} = Z^c \begin{pmatrix} P \\ M \\ X \\ 1 \end{pmatrix}$$

3.2 Closed-loop differential game

In this section, we look for a Nash closed-loop equilibrium. We want to characterize the behaviour of both countries when they act without cooperating[9]. Each country seeks to minimize:

$$\int_0^\infty (y'Q_i y + v_i' R v_i) dt$$

subject to:

$$\dot{y} = Ay + B^m_i v_i + B^m_j v_j \, j \neq i$$

with

$$v_i(t) \equiv e^{-\frac{1}{2}\rho t} \begin{pmatrix} \frac{X}{2\sqrt{\beta_2}} - \frac{\beta_{i,1}}{2\sqrt{\beta_2}} + \frac{P}{2\sqrt{\beta_2}} + \sqrt{\beta_2} E_i \\ I_i \end{pmatrix}$$

[9]The only cooperation assumed here is about the choice of stabilizing strategies.

$$B_i^m \equiv \begin{pmatrix} \frac{\zeta}{\sqrt{\beta_{i,2}}} & 0 \\ \frac{1}{\sqrt{\beta_{i,2}}} & 0 \\ 0 & \sigma \\ 0 & 0 \end{pmatrix} ; R^m \equiv \begin{pmatrix} 1 & 0 \\ 0 & \gamma \end{pmatrix} ; S_i^m \equiv B_i^m R^{m\,-1} B_i^{m\prime}$$

$$Q_i^m \equiv \begin{pmatrix} -\frac{1}{4\beta_{i,2}} & 0 & -\frac{1}{4\beta_{i,2}} & \frac{\beta_{i,1}}{4\beta_{i,2}} \\ 0 & \alpha_i & 0 & 0 \\ -\frac{1}{4\beta_{i,2}} & 0 & -\frac{1}{4\beta_{i,2}} + \eta_{i,2} & \frac{\beta_{i,1}}{4\beta_{i,2}} - \frac{1}{2\eta_{i,2}} \\ \frac{\beta_{i,1}}{4\beta_{i,2}} & 0 & \frac{\beta_{i,1}}{4\beta_{i,2}} - \frac{1}{2\eta_{i,2}} & -\frac{\beta_{i,1}^2}{4\beta_{i,2}} \end{pmatrix}$$

In this setting, as shown in Engwerda (2005), the markovian linear strategy, for player i, is given by:

$$v_i^m = C_i^m y$$

where $C_i^m = -R^{m\,-1} B_i^{m\prime} K_i^m = \begin{pmatrix} c_i^m(1,1) & \cdots & \cdots & c_i^m(1,4) \\ c_i^m(2,1) & \cdots & \cdots & c_i^m(2,4) \end{pmatrix}$ and K_i^m, $i = 1,2$ are the symmetric stabilizing solutions of the following system of algebraic Riccati equations[10]:

$$\begin{array}{c} (A - S_2^m K_2^m)' K_1^m + K_1^m (A - S_2^m K_2^m) - K_1^m S_1^m K_1^m + Q_1^m + K_2^m S_2^m K_2^m = 0 \\ (A - S_1^m K_1^m)' K_2^m + K_2^m (A - S_1^m K_1^m) - K_2^m S_2^m K_2^m + Q_2^m + K_1^m S_1^m K_1^m = 0 \end{array} \quad (4)$$

Let's define C^m and v^m as:

$$C^m = \begin{pmatrix} c_1^m(1,1) & \cdots & \cdots & c_1^m(1,4) \\ c_2^m(1,1) & \cdots & \cdots & c_2^m(1,4) \\ c_1^m(2,1) & \cdots & \cdots & c_1^m(2,4) \\ c_2^m(2,1) & \cdots & \cdots & c_2^m(2,4) \end{pmatrix} ; \mathrm{v^m} = C^m y$$

Like in the previous section, a transformation has to be done in order to interpret the results. Z^m is defined as:

$$Z^m = TR_2 \left(C^m - TR_1 \right) = \begin{pmatrix} z_{1,1}^m & \cdots & \cdots & z_{1,4}^m \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ z_{4,1}^m & \cdots & \cdots & z_{4,4}^m \end{pmatrix}$$

[10]The algorithm used to solve for this system is described in ANNEX 1.

such that the markovian strategies are given by:

$$\begin{pmatrix} E_1^m \\ E_2^m \\ I_1^m \\ I_2^m \end{pmatrix} = Z^m \begin{pmatrix} P \\ M \\ X \\ 1 \end{pmatrix}$$

4 Monte Carlo procedure

4.1 First-best simulation strategy

A complete solution of the model would express each endogenous variable of the model as a function of the set of parameters. Unfortunately, such a solution is very hard, if possible, to compute. Let $f_i(\pi)$ be the function that gives the endogenous variable ϕ_i and π the set of the N exogenous parameters indexed by k. A Monte Carlo procedure enables to give a Taylor approximation of f_i for a range of parameters values. Indeed, for a given π, simple algorithms compute the particular solution of the model. We run 1000 simulations, choosing randomly π_j for each iteration j. Let's call $\bar{\phi}_i$ the average value of ϕ_i in the sample. Then, we compute the OLS estimators $\hat{\psi}$ of the set of parameters ψ of the following function:

$$\phi_i = \psi_{1,i} + \sum_{k=1}^{N} \psi_{(k+1,i)}\pi_k + \sum_{k=1}^{N}\sum_{k' \geq k} \psi_{(k,k',i)}\pi_k\pi_{k'} + e_i \tag{5}$$

where e is an error term[11].

For each iteration, the parameters are chosen via an homogeneously distributed density function defined between $0.5\mu_{\pi_i}$ and $1.5\mu_{\pi_i}$ where μ_{π_i} is the mean value of π_i.

Unfortunately, until now, every attempt to perform those numerical computations have failed. The reason is that the computer takes the matrix to be inverted in the ols method[12] to be singular. We then decide to adapt our simulation strategy towards a less demanding objective.

4.2 Second-best simulation strategy

In our second-best simulation strategy, we remove all the squares and the 2*2 interactions in the equation 5. This leaves us only with the coefficients

[11]Notice that the error term is treated as random, even if it's not: it is the difference between the genuine deterministic function and its Taylor approximation.

[12]Namely, $(\nu'\nu)$, where ν is the matrix of exogenous variables.

of the 14 parameters, plus a constant. The endogenous variables are the 16 components of both the matrix Z^c and Z^m, the state of the stocks after 10 periods (which represents a relevant future), the state of the stocks after 600 periods (which represents the steady state of the model), and the intertemporal welfare computed over the 10 first periods, both for the cooperative equilibrium and the markovian equilibrium.

5 Results

5.1 General Results

As noted previously, we discriminate between two different study-cases depending on the relative countries' sensitiveness to environmental damages. In the first case (referred to as Case 1), the poor country is supposed to display the greatest sensitiveness to environmental damages ($\alpha_1 < \alpha_2$). In the second case (referred to as Case 2), the rich country is the one which displays the greatest sensitiveness to environmental damages ($\alpha_1 > \alpha_2$).

The results are presented from Table 1 to 6[13]. The first two tables (Table 1 and table 2) display the Cooperative equilibrium, respectively, for Case 1 and Case 2. The next two tables (Table 3 and table 4) present the equilibrium issues of the Markovian game, respectively for Case 1 and Case 2. Figures in bracket represent the percentage of iterations where the absolute value for the corresponding component in the Markovian strategy is greater than the absolute value for the same component in the Cooperative equilibrium. Finally, the last two tables (Table 5 and table 6) display , respectively for Case 1 and Case 2, the welfare for each country (designed by $W_i(10), i = 1, 2$) and the aggregated welfare after 10 years, in cooperative and markovian equilibrium, and the value of the three stocks after 10 and 600 years.

Three noticeable features of the model emerge from tables 1 to 6. First, any increase in the oil price, the pollution stock and the stock of knowledge induce lower emissions. This result holds for 100% of the simulations. It simply reflects the fact that the three stocks increase the cost of using oil: the direct private cost (price), the external cost (pollution) and the opportunity cost (knowledge). This effect is however reinforced when the richest country is the more sensitive to environmental damage (This can be seen by comparing the marginal impacts from the three stocks across Case 1 and Case 2).

Second, in the cooperative equilibrium, the same level of R&D investment is required in the poor and in the rich countries: from that point of view, the solution is egalitarian rather than equitable. However, this result comes

[13]See tables in annex A.

from the assumption that both countries have the same cost of investment in research activity (γ is identical for the two countries), and would not hold otherwise. Third, in the cooperative equilibrium, both in Case 1 and in Case 2, the most important emissions come from the more technologically efficient country, i.e. Country 1.

Let us now turn to two important results. The first one concerns the relative welfare gains between the cooperative and the noncopperative outcome while the second one concerns the relative levels of R&D spending between both those alternative outcomes.

Considering first welfare issues, an interesting result emerges from the comparison of welfare gains after 10 years. As expected, the aggregated welfare is always greater in the cooperative outcome compared to the Markovian one. However, from a national point of view, the cooperative equilibrium is preferred to the Markovian one by the two nations only in Case 2, namely when the richest country is also the most sensitive to environmental damage. In this case, indeed, the adoption of free riding strategies always leads to a decrease in both welfares. On the contrary, in Case 1, only the poor country which is also the most sensitive to environmental damage) has an advantage to cooperate. The welfare of Country 1 increases in the Markovian outcome compared to the Cooperative one. This result can explain why some industrialized countries are reluctant to ratify international agreements on Climate Change such as the Kyoto Protocol.

A closer examination of the impacts of the three stocks on oil consumption helps to explain why the adoption of free riding strategies in the Markovian game is likely. First, note that, in both Case 1 and Case 2, the variations are small (in absolute values) for the country that is the most sensitive to environmental damage and large for the other country[14].

Second, the negative impact of pollution on the emissions is stronger in the cooperative game compared to the Markovian game. Indeed, in the cooperative game, each player takes into account the negative impact of pollution not only on its own situation, but also on the situation of the other player. It can be added that the difference is rather important for the country that is less sensitive to the environmental damages. This reflects the idea that the adoption of free riding strategies in the Markovian game primarily comes from the behaviour of the less sensitive country[15]. Third, a similar

[14] Indeed, the cooperative equilibrium is closer to the individual preferences of the most sensitive country.

[15] Indeed, $\frac{\bar{z}^c_{1,2}}{\bar{z}^m_{1,2}} = 9,86$ in Case 1 and $\frac{\bar{z}^c_{2,2}}{\bar{z}^m_{2,2}} = 10,03$ in Case 2. $z^c_{i,2} > z^m_{1,2}$ is true in 100% of the simulations, for i=1 in Case 1 and i=2 in Case 2. Morever, the difference is unimportant for the country which is the most sensitive to the environmental damage

argument holds developed concerning the impact of the knowledge stock over the emissions. This impact is weaker for the less environmental sensitive country (in 98% of the simulations in Case 1 and in 98,4% of the simulations in Case 2) and is stronger for the most environmental sensitive country (in 100% of the simulations for the two cases). Moreover, the amplitude of the variations is lower for the most sensitive country compared to the less sensitive one. Finally, the impact of oil price on oil consumption is stronger in the Markovian game than in the Cooperative game for the two countries, with the most important variation for the less sensitive environmental countries. To understand the deep reason behind this over-reaction to the oil price on oil consumption, one need however to acknoweldge the second main result of our research.

Our second striking result is that the aggregate level of R&D expenditures is lower under the cooperative outcome compared to the non-cooperative one. In other words, an agreement based on both R&D and emission cutting reduces the aggregate cumulative R&D expenditure. We call this effect the "paradox of knowledge". On the one hand, the public good nature of the knowledge implies that, *ceteris paribus*, the aggregate R&D expenditure is higher in the cooperative case than in the non cooperative case. But, on the other hand, in the cooperative case, both the stock of pollution and the oil prices are small compared to the non cooperative case (Cf. table 5 and table 6). The private incentives to invest in research are then higher in the non-cooperative equilibrium as knowledge improvements are what allow to offset higher oil prices and higher levels of pollution. Of course, the cooperative outcome remains a better outcome even if it implies less research. Finally, this "knowledge paradox" also help to explain why oil consumption over-reacts to oil price under the Markovian game. Indeed, the players know that a Markovian game lead to an over-investment in knowledge, which allows to substitutes more production by the output of research sector to the emissions in presence of an increase in the oil price.

This result has also strong normative implications. It indeed offers a counter-argument to the view that increasing the amounts of R&D spending on low-carbon technology should be considered as a key criteria in any future agreement. From this perspective, our result generalizes a previous implication by the model by van der Ploeg and de Zeeuw (1994), according to which, in the absence of international coordination for pollution control, levels of clean technology stocks are too excessive. This implication also holds in our setting. Let us examine the impacts of the three stocks on the level

($\frac{\bar{z}^c_{i,2}}{\bar{z}^m_{i,2}} = 1,03$ for i=2 in Case 1 and i=1 in Case 2 and $z^c_{i,2} > z^m_{1,2}$ is true for only 74,6% of the simulations for i=2 in Case 1 and for 71,5% of the simulations for i=1 in Case 2).

of R&D investment. First, in Case 1 and Case 2, the investments by both countries are less sensitive to the stock of knowledge. Second, in both cases, the less environmentally sensitive country knows that the other player has to invest more in case of an increase of the pollution stock. In consequence, the less sensitive country can invest less in reaction to this increase (in fact, the impact of the stock pollution becomes negative for the less environmental sensitive country in the Markovian game). On the other hand, the most environmentally sensitive country knows that the other country has, in a Markovian game, a lower reaction in the presence of an increase of the stock pollution in term of investment, compared to the optimum, so this country must increase his own reaction in order to compensate the behavior from the other country (as it can be seen, in the two cases, the impact of the pollution stock on investment is, in absolute value, larger in the Markovian game compared to the Cooperative equilibrium, for the most environmental sensitive country). An opposite argument, in terms of countries, explain the fact that the sign of the impact of the oil price on investment becomes negative for the most environmental sensitive country and increases in absolute value (for a majority of simulations) for the less environmental sensitive country.

In order to go deeper in the analysis, we now proceed to some static comparative exercises. We investigate the impact of changing the value of key parameters on the coefficients of the regressions explained in section 4. The large number of coefficients does not however allow us to study each of them in a systematic way. We rather select the most salient effects.

5.2 On Chinese growth

The non-inclusion of emerging countries such as China is an important critic addressed to the Kyoto protocol by the United States. In this subsection, we study the impact of an increase in the wealth of the poor country (through an increase of $\beta_{2,1}$ and $\eta_{2,1}$) on the relevant variables. The results are presented in tables 7 to 18. For all the tables hereafter, number in bracket represents the Student's t statistics associated to the corresponding variation.[16]

Tables 10 and 11 show that when the growth of the poor country occurs by the mean of an increase in its emissions' productivity (through parameter $\beta_{2,1}$), it always induces a significant welfare loss for the rich country. This welfare loss is larger when the rich country is also the most sensitive to environmental damage (Case 2). On the other hand, the welfare of the poor country does not necessarily increase. Tables 7 and 8 clearly show than an

[16] In order to have a P-value never greater than 15% we only comment absolute values above 1,5.

increase in $\beta_{2,1}$ leads to an increase of the welfare of Country 2 only when this country is the less sensitive to environmental damage(Case 2). In the opposite case, i.e when the poor country is very sensitive to environmental damage (Case 1), an increase in its wealth through $\beta_{2,1}$ paradoxically lowers the welfare of both economies.

At the aggregated level, it is also noticeable that the increase in the wealth of the poor economy through $\beta_{2,1}$, does not necessarily lead to a significant increase in aggregated emissions, and consequently, to a significant increase in the global pollution stock. Global emissions increase only after 10 years in the Markovian game of Case 1 and after 10 and 600 years for the Markovian game of Case 2. This result can be explained as follows. On the one hand, an increase of $\beta_{2,1}$ lowers the impact of some of the three stocks on emissions (especially the impact of the knowledge stock on emissions for Case 1 and the impact of the pollution stock on emissions of country 2 in Case 2 in the Markovian equilibrium) and increases the emissions' constant of the Country 2. But at the same time, it reduces the emissions' constant of Country 1 and this can lead to a reduction of the Country 1 emissions. The likelihood of a decrease in aggregated emissions is reinforced by the decrease of oil price, in both Case 1 and 2, in the Cooperative equilibrium. This reflects the fact the the pressure on the oil market is lower under the Cooperative equilibrium. In terms of R&D investment, as shown by tables 9 and 10, an increase in $\beta_{2,1}$ has only little impact.

In sum, the rich country always suffer from an increase in the wealth of the poor economy driven by improvements in its emissions' productivity. Moreover, the rich country loses more in the Cooperative equilibrium when the poor country is also the more sensitive to environmental damage (Case 1) and in the Markovian game when the rich country is the most sensitive to environmental damage (Case 2).

If we turn now to the case where the increase in the wealth of the poor country is driven by parameter $\eta_{2,1}$ things change substantially. Specifically, the rich country is less likely to suffer from the wealth improvement of the poor economy while welfare gains are warranted for the poor country. This result can be explained as follows. First, as shown by tables 17 and 18, an increase of $\eta_{2,1}$ leads to an increase of the knowledge stock[17]. It also leads to a reduction, in the cooperative equilibrium, of the impact of the pollution stock on emissions when the poor country is the most environmental sensitive and to an increase of the impact of the oil price on the emissions when the

[17]This result is due to an increase in the investment constant for both countries in the Cooperative equilibrium and to an increase of the investment constant for Country 2 that overcompensates the decrease of the investment constant for Country 1 in the Markovian game.

poor country is the least environmental sensitive. In terms of Welfare, the poor country always gains while the rich country looses only in Case 1 for the Markovian equilibrium.

5.3 On inequality growth

In the previous section, we have studied the impact of a reduction in the wealth gap between the poor and the rich countries. In this section, we investigate the opposite case, i.e. the case of a widening of the wealth gap between the two groups of countries. One can think, for instance, to the relative position of some African countries in comparison to the industrialized world. To investigate this issue, we consider how an increase in the wealth of the rich country (either driven by an increase of $\beta_{1,1}$ or by an increase in $\eta_{1,1}$) affects the relevant variables. Our main results are presented in tables 19 to 30 below.

The impact of an increase of $\beta_{1,1}$ is rather simple to understand. Whatever the relative sensitiveness of the countries to the environment, an increase in $\beta_{1,1}$ leads to an increase in the emissions of Country 1 and to a decrease in the emissions of Country 2 (through its impact on the emissions constants). At an aggregate level, this leads to an increase of emissions as it can be seen through the increase of the oil price and of the pollution stock after 10 and 600 years.

In terms of R&D investment, the impact of the oil price and of the pollution stock is lowered for both countries in the Cooperative equilibrium and in the Markovian game as long as the rich country is the less sensitive to environmental damage. Moreover, the increase of $\beta_{1,1}$ does not significantly impact the knowledge stock whatever the type of equilibrium and whatever the relative sensitiveness of countries 1 and 2 to the environment.

Finally, tables 23 and 24 show the impacts in terms of welfare. An increase in $\beta_{1,1}$ always leads to welfare gains for the rich country and to welfare looses for the poor country. This result is amplified when the poor country is the most sensitive to environmental damage.

The impact of an increase of in $\eta_{1,1}$ is studied in tables 25 to 30. Unexpectedly, an increase in $\eta_{1,1}$ does not have any significant impact on the emissions, on the oil price and on the pollution stock. In other words, there is no substitution between dirty and clean technologies when the rich country increases its wealth by the way of an increase of its productivity in terms of use of stock knowledge. Indeed, the effects are concentrated on the investment by the two countries and on the knowledge stock: in the Cooperative equilibrium, the two countries increase their R&D investments (as it can be seen by examining the investment constants). Moreover, in both Case 1 and

Case 2, and in Markovian game, in compliance with free riding strategies, Country 2 decreases its R&D investment. Indeed, Country 2 knows that Country 1 has to increase its own investment, and Country 1 increases its investment more strongly than in the Cooperative equilibrium, because it knows that Country 2 has to decrease its own investment. Those effects lead to an increase of the knowledge stock except for the first periods under Case 1.

In term of welfare, an increase in $\eta_{1,1}$ is more equitable than an increase in $\beta_{1,1}$ because it improves the welfare of the rich country without harming the poor country. Actually, the poor country experiment welfare gains in all cases except one: in the Markovian equilibrium when the rich country is the most sensitive to environmental damage.

5.4 The Impact of an increase in environmental concerns

We have now to study the impacts of an increase of environmental concerns. We distinguish the two possible cases: an increase in environmental concerns for the rich country (increase of α_1) and for the poor country (increase of α_2). The results are summarized in table 31 to 42.

As expected, in the Cooperative equilibrium, an increase of the concern for environmental damages, whatever the country that is the more environmental sensitive, always leads to an increase, in absolute value, in the impact of the pollution stock on the emissions. In some situations, still for the Cooperative equilibrium, this increase, which reflects an increase of the external cost (pollution) is partly compensated by a significantly decrease in the impact of the oil price on the emission (this can be checked in all situations except for an increase of the richest country environmental concern when the poorest country is the more environmentally sensitive), reflecting a decrease in the opportunity direct private cost in regard to the external cost, and, for an increase of the richest country environmental concern when he is already the more environmental sensitive, by a reduction of the impact of the knowledge stock on the emissions, reflecting a decrease of the opportunity cost of knowledge in terms of external cost. An increase in the environmental concern of one of the countries leads to a decrease in the constant of emissions for both countries when this country is the more environmental sensitive. It leads to a decrease in the constant of emissions of the poor Country in both cases when this country is the less environmental sensitive. This can be explain, for an increase of α_1 in Case 1, by the fact that the technological advantage of the Country 1 prate in the sense of the option to decrease the constant emissions of Country 2, because it is the more efficient, by comparison of the opportunity cost. In terms of investment in the knowledge stock, in the Cooperative equilibrium, there is also always an increase of the impact of the pollution stock on the investment in response to an increase in the environmental concerns. As for the emission, this increase is partially compensated by a significant decrease in the impact of the oil price on the emissions, in all situations except for an increase of the richest country environmental concern in case 1.

In the Markovian game, the results are complicated by the presence of free riding strategies. In terms of emissions, an increase in the environmental concern for a country always results in an increase in the impact of the pollution stock on his own emissions. When the country is the more environmental sensitive, this increase is straightened in both cases by a decrease in the impact of the oil price and of the knowledge stock on his own emissions. The decrease of the oil price on the poor country emissions after an increase of α_2 is also present in Case 2. In response, the other country can either lower the impact of the pollution stock on the emission (rich country strategies in front of an increase of α_2) or the impact of the oil price in the emission (poor country strategies when he is at before the increase of α_1 the more environmental sensitive) or lower the impact of the two stocks (poor country strategies in front of an increase of α_1 in Case 2). In terms of emissions constant, it is lowered by the rich country after an increase of α_1 only in case 2 and by the poor country after an increase of α_2 in both cases. After an increase of α_2, when the rich country is before the increase the less environmental sensitive, he is taking advantage to that increase for lowering his own constant emission.

In terms of investments, in the Markovian game, when the environmental concern of the richest country is increased but that the more environmental sensitive country is the poorest one, the result his a relatively more virtuous situation since there is for the two countries a decrease of the impact of oil price on investment and an increase of the impact of the pollution stock on investment. This is because, in this case, there is a partial reconciliation between the concerns of both countries: the more technologically efficient country, the richest one, and the more environmental sensitive, the poorest one. Moreover, this mechanism is necessary as a partial counterpart of the excessive presence of non-socially efficient strategies as it can be seen by the examination of the evolution of stocks. Indeed, when the the pollution stock is affected by the increase in the environmental concern of one country (which is always the case after 10 years and two time after 600 years), the change is always negative, except after 600 years for the case examined here. In the three other cases there is a reinforcement of the free riding strategies:

the negative or positive impacts of both the oil price and of the pollution stock on investment are always increased. This is confirmed by the fact that the investment constant of the country for which the environmental concern increases when he is the more environmental sensitive increased (Cf. Table 34 and 39), whereas the investment constant for the other country decreases.

As may be expected, the welfare of both countries are always lowered by an increase of the environmental concerns for one of this countries in the Cooperative equilibrium except for the welfare of the poor country in Case 1 which is not significantly affected by an increase of α_1. In the Markovian game, the welfare of the country which experiences a raise in his environmental concern is always lowered and, by the means of the adoption of free riding strategies, the welfare of the other country is always improved except in the case of an increase of α_2 in Case 1, the welfare of the rich country is not significantly affected. To complete the analysis of an impact of an increase of one country environmental concerns, it should be noted that the oil price, is always decreased after 10 and 600 years.

5.5 The impact of an increase in the rate of pollution decay

It is well-known since the seminal work by Forster [18], that an increase in the rate of pollution decay does not affect unambiguously the pollution stock. It rather has two opposite effects on the pollution stock. On the one side, it reduces the pollution stock as it increases the free cleaning contribution of the environment. On the other side, it increases the pollution stock as the additional free cleaning contribution reduces the environmental concerns bound to the presence of the pollution stock in environment, which leads to greater production and additional waste. The pollution stock can therefore be increased or decreased depending on the relative weight of the two effects.

The presence of these counterbalancing forces can be checked in Tables 43 to 48. In particular, we show that an increase in the rate of pollution decay induces a direct increase of emissions in all situations. Indeed, when the constants emissions are significantly affected, the sign is always positive. Moreover, in all cases, the impact of the pollution stock on emissions decreases, and in some cases, the impact of oil price on emissions increases. Consequently, the oil price increases in all cases after 10 and 600 years. Similar mechanisms lead to a decrease in the knowledge stock when the latter impact is significant.

Our main result remains however that the second effect is overwhelmed

[18] Cf. Forster (1975) and Forster (1977).

by the first one for all situations. Consequently, an increase in the rate of pollution decay in our model unambiguously improves the welfare of both countries and reduces the pollution stock after 10 and 600 years.

5.6 The impacts of an increase in the discount rate

The use of discount rates in long-run environmental and natural resource use problems is a controversial issue. The basic concern is that too high discount rates can lead to intergenerational conflicts. In particular, they may over-weight the welfare of the present generations to the detriment of future generations (see e.g. Howarth (1996)). Moreover, in the context of our current research, the discount rate tends to increase the opportunity cost of the knowledge cost (which require actual investment for a future use) in regard to the use of the "dirty" production technology. Those intuitions are confirmed by the results in Tables 49 to 54. As shown by tables 49 and 50, an increase in the discount rate leads to i) an increase in the emission constant for both countries, ii) an increase in the impact of the variable reflecting the direct private cost of the use of the "dirty technology" (oil price) on emissions, iii) a decrease in the impact of the pollution stock on the level of emissions, and iv) a decrease in the impact of the knowledge stock on emissions (only in Case 2). In terms of R&D investment, an increase in the discount rate leads to an increase in the impact of oil price on R&D investment in the Cooperative equilibrium and to a decrease in this impact in the Markovian game. It also leads to a decrease in the impact of the pollution stock on R&D investment in both cases, to a decrease in the investment constants in a majority of situations and to a decrease in the impact of the knowledge stock on R&D investment.

As a result, there is an increase in the oil price after 10 and 600 years for all the situations, an increase in the pollution stock after 10 years and a decrease after 600 years for Case 2 (in Case 1 the pollution stock is not significantly affected after 600 years) and a decrease in the stock of knowledge after 10 years.

The discount rate seems also to be important in terms of intragenerational transfers. Tables 53 and 54 show that an increase in the discount rate leads to an increase in the welfare for both countries only in Case 2, i.e. when the rich country is also the most sensitive to environmental damage. In the alternative Case 1, the welfare of the rich country improves while the the poor country experiments a worsening of its welfare. Those results hold both for the Cooperative equilibrium and for the Markovian game.

5.7 The impacts of an increase in the cost of investment

The impacts of an increase in the cost of investment are shown in tables 55 and 56 below. Paradoxically, an increase in the cost of investment has little impact on the level of emissions. It however affects substantially the level of R&D investment. Whatever the relative environmental concerns and the type of game the nations are involved in, the impacts of each of the three stocks on the level of R&D investment are all lowered by an increase in the cost of investment[19]. The investment constants are also always lowered.

An even more surprising result is that the increase in the cost of investment has little impact in terms of the stock of knowledge and in terms of welfare: the only effects which are significant are an increase in the welfare of the poor country in Case 2 and a decrease in the stock of knowledge after 10 years in Case 1.

6 Conclusion

In this paper, we studied the problem of international coordination in Climate policy using a three state-variables (oil price, pollution and knowledge), two asymmetric countries (a rich one and a poor one) differential game with Markov-linear strategies. Unfortunately, purely analytic solution of this kind of games cannot be found. We use a Monte Carlo procedure to get an insight into the behavior of the model. This allows us to make a study in terms of emission and investment strategies, of state of the three stocks and of countries' welfare. We also proceeded to some static comparative exercises for the more relevant parameters. We distinguished two cases regarding the relative countries' sensitiveness to environmental damages: in the first case, the poor country whose supposed to be the more environmental sensitive, while the opposite is assumed in the second case.

This study puts in light the "paradox of knowledge": while knoledge is a public good, the non-cooperative equilibrium displays a higher level of R&D expenditures than the optimal path. This over-investment in R&D is a reaction to the increase in the oil price that is faster along the non cooperative equilibrium than along the optimal path. This paradox questions the assertion that R&D spending on low-carbon technology should be a key feature of any further agreement.

[19]The only exception is the impact of the oil price on the investment of the poor country in Case 1 which is not significantly altered.

Static comparative results also put into light several points regarding the current debates about Climate Change, such as the question of the non-inclusion of emerging countries like China to the Kyoto protocol. We find that an increase of poor country's wealth by the mean of an increase of his emissions' productivity always leads to a welfare loss for the rich country, sometimes to a welfare loss for the poor country (when he is the most sensitive to environmental damage) but does not necessary lead to a significant increase in the global pollution stock. By comparison, if increase of poor country's wealth proceed from an increase of his use of clean technology abilities, the rich country is less likely to suffer from the wealth improvement of the poor economy, while welfare gains are warranted for the poor country.

To refine the analysis, we should go beside the linear regression used here, in order to test the impact of interactions between couples of parameters, and the squares of some of these parameters: this is part of our research agenda.

A Tables

A.1 Mean values of the endogenous variables

	dP	dM	dX	Cte
dE_1^c	-1,63E-03	-8,08E-03	-2,69E-03	9,37
dE_2^c	-1,63E-03	-8,08E-03	-2,69E-03	3,90
dI_1^c	5,99E-04	2,95E-03	-7,08E-01	72,5
dI_2^c	5,99E-04	2,95E-03	-7,08E-01	72,5

Table 1: Equilibrium strategies: the Cooperative equilibrium in Case 1

	dP	dM	dX	Cte
dE_1^c	-1,65E-03	-8,19E-03	-2,73E-03	9,51
dE_2^c	-1,65E-03	-8,19E-03	-2,73E-03	3,92
dI_1^c	6,10E-04	2,99E-03	-7,09E-01	72,8
dI_2^c	6,10E-04	2,99E-03	-7,09E-01	72,8

Table 2: Equilibrium strategies: the Cooperative equilibrium in Case 1

	dP	dM	dX	Cte
dE_1^m	-2,39E-03 (100%)	-8,19E-04 (0%)	-2,75E-03 (100%)	12 (100%)
dE_2^m	-1,88E-03 (99%)	-7,84E-03 (25,4%)	-2,67E-03 (2%)	5,28 (99,7%)
dI_1^m	6,72E-04 (60,5%)	-2,26E-03 (1,9%)	-4,08E-01 (0%)	39,4 (0%)
dI_2^m	-3,02E-05 (2,7%)	5,94E-03 (100%)	-4,08E-01 (0%)	44,2 (0%)

Table 3: Equilibrium strategies: the Markovian game in Case 1

	dP	dM	dX	Cte
dE_1^m	-1,90E-03 (98,8%)	-7,98E-03 (28,5%)	-2,71E-03 (1,6%)	10,1 (94,6%)
dE_2^m	-2,43E-03 (100%)	-8,16E-04 (0%)	-2,79E-03 (100%)	7,34 (100%)
dI_1^m	-3,38E-05 (2,9%)	6,03E-03 (100%)	-4,08E-01 (0%)	42,5 (0%)
dI_2^m	6,87E-04 (61,5%)	-2,30E-03 (1,7%)	-4,08E-01 (0%)	41,7 (0%)

Table 4: Equilibrium strategies: the Markovian game in Case 1

	$W_1(10)$	$W_2(10)$	$\sum_{i=1,2} W_i(10)$
Cooperative equilibrium	1,76E+05	-4,86E+05	-3,10E+05
Markovian equilibrium	3,56E+05 (100%)	-5,60E+05 (96,4%)	-2,04E+05 (100%)
	$P(10)$	$M(10)$	$X(10)$
Cooperative equilibrium	448	709	116
Markovian equilibrium	582 (100%)	773 (100%)	126 (85,9%)
	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	3400	212	111
Markovian equilibrium	4360 (96,8%)	176 (18,5%)	120 (93,5%)

Table 5: Various value after 10 and 600 years: Case 1

	$W_1(10)$	$W_2(10)$	$\sum_{i=1,2} W_i(10)$
Cooperative equilibrium	-3,71E+05	6,41E+04	-3,07E+05
Markovian equilibrium	-4,19E+05 (92%)	1,49E+05 (99%)	-2,70E+05 (100%)
	$P(10)$	$M(10)$	$X(10)$
Cooperative equilibrium	448	709	116
Markovian equilibrium	548 (100%)	756 (100%)	123 (85,1%)
	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	3400	213	111
Markovian equilibrium	3620 (87,6%)	177 (2,9%)	119 (88,1%)

Table 6: Various value after 10 and 600 years: Case 2

A.2 Impact of the growth in the poor country

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	2,66E-08 (1,32)	1,09E-07 (9,24E-01)	6,86E-08 (1,57)	-8,39E-04 (-6,86)	2,66E-08 (1,32)	1,09E-07 (9,24E-01)	6,86E-08 (1,57)	2,19E-03 (3,56)
Markovian equilibrium	1,18E-05 (1,72)	3,71E-06 (8,10E-01)	1,47E-05 (1,68)	-5,89E-02 (-2,19)	8,33E-06 (1,3)	3,16E-05 (8,49E-01)	1,40E-05 (1,55)	-2,28E-02 (21,6)

Impact of $\beta_{2,1}$ on the emissions, Case 1

Table 7:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-1,00E-08 (-4,86E-01)	3,95E-09 (3,44E-02)	3,36E-08 (7,63E-01)	-6,28E-04 (-4,91)	-1,00E-08 (-4,86E-01)	3,95E-09 (3,44E-02)	3,36E-08 (7,63E-01)	2,33E-03 (35,9)
Markovian equilibrium	3,02E-08 (1,03)	-7,63E-08 (-5,78E-01)	3,51E-08 (8,07E-01)	-3,99E-04 (-2,65)	4,56E-09 (1,30E-01)	3,08E-08 (1,9)	3,12E-08 (6,80E-01)	2,41E-03 (21,5)

Impact of $\beta_{2,1}$ on the emissions, Case 2

Table 8:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	7,75E-10 (-1,12E-08)	-1,89E-08 (1,51E-08)	5,66E-06 (3,21E-06)	6,29E-04 (9,63E-04)	7,75E-10 (1,51E-08)	-1,89E-08 (-4,52E-08)	5,66E-06 (3,22E-06)	6,29E-04 (-2,04E-04)
Markovian equilibrium	-1,12E-08 (7,09E-02)	1,51E-08 (-2,79E-01)	3,21E-06 (1,01)	9,63E-04 (8,32E-01)	1,51E-08 (7,09E-02)	-4,52E-08 (-2,79E-01)	3,22E-06 (1,01)	-2,04E-04 (8,32)

Impact of $\beta_{2,1}$ on the investments, Case 1

Table 9:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,08E-08 (-8,84E-01)	2,56E-08 (4,02E-01)	2,42E-06 (4,34E-01)	-7,81E-04 (-1,04)	-1,08E-08 (-8,84E-01)	2,56E-08 (4,02E-01)	2,42E-06 (4,34E-01)	-7,81E-04 (-1,04)
Markovian equilibrium	-3,64E-08 (-1,94)	1,51E-07 (9,89E-01)	1,41E-06 (4,40E-01)	4,19E-04 (8,69E-01)	1,60E-08 (8,63E-01)	-8,86E-08 (-1,29)	1,42E-06 (4,41E-01)	-1,28E-03 (-2,66)

Impact of $\beta_{2,1}$ on the investments, Case 2

Table 10:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-23,9 (-4,97)	11,3 (4,06)	-7,53E-03 (-2,73)	-3,87E-03 (-4,11)	3,10E-03 (1,16)	-2,29E-01 (-8,08)	-8,08E-03 (-1,93)	1,24E-03 (6,44E-01)
Markovian equilibrium	-12,1 (-2,43)	17,4 (4,32)	5,01E-03 (1,27)	1,28E-03 (8,95E-01)	3,24E-03 (1,18)	-1,20E-03 (-4,94E-02)	1,42E-02 (1,64)	2,03E-03 (8,26)

Impact of $\beta_{2,1}$ on different values, Case 1

Table 11:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-1,84E+01 (-3,70)	4,77 (2,5)	-7,56E-03 (-2,73)	-2,11E-03 (-2,03)	-2,16E-03 (-8,44E-01)	-2,22E-01 (-8,16)	-6,93E-03 (-1,58)	-1,80E-03 (-9,68E-01)
Markovian equilibrium	-3,79E+01 (-6,39)	7,17E+01 (32,9)	2,99E-02 (6,9)	1,73E-02 (11,7)	-5,04E-04 (-1,92E-01)	1,69E-01 (7,4)	-1,44E-02 (-3,16)	-2,04E-03 (-8,49E-01)

Impact of $\beta_{2,1}$ on different values, Case 2

Table 12:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	2,48E-08 (8,28E-02)	4,06E-06 (2,31)	9,64E-07 (1,49)	-1,56E-03 (-8,58E-01)	2,48E-08 (8,28E-02)	4,06E-06 (2,31)	9,64E-07 (1,49)	1,96E-03 (2,14)
Markovian equilibrium	7,62E-07 (1,46)	2,71E-07 (1,06)	1,12E-06 (1,65)	-4,30E-03 (-1,64)	2,35E-07 (5,49E-01)	4,30E-06 (2,17)	8,99E-07 (1,41)	3,75E-04 (2,68E-01)

Impact of $\eta_{2,1}$ on the emissions, Case 1

Table 13:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-5,3E-07 (-1,7)	1,6E-06 (8,9E-01)	-4,1E-07 (-6,0E-01)	2,1E-03 (1,1)	-5,3E-07 (-1,7)	1,6E-06 (8,9E-01)	-4,1E-07 (-6E-01)	2,3E-03 (2,4)
Markovian equilibrium	-5,5E-07 (-1,2)	2,0E-06 (1)	-4,5E-07 (-6,7E-01)	2,5E-03 (1)	-4,3E-07 (-8E-01)	-3,0E-08 (-1,2E-01)	-3,7E-07 (-5,3E-01)	1,6E-03 (9,3E-01)

Impact of $\eta_{2,1}$ on the emissions, Case 2

Table 14:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	1,10E-07 (6,77E-01)	-6,21E-07 (-6,19E-01)	-3,47E-05 (-4,18E-01)	1,91E-01 (17)	1,10E-07 (6,77E-01)	-6,21E-07 (-6,19E-01)	-3,47E-05 (-4,2E-01)	1,91E-01 (17)
Markovian equilibrium	-1,60E-07 (-5,81E-01)	6,44E-08 (6,32E-02)	-1,99E-05 (-4,16E-01)	-1,89E-01 (-26,3)	3,30E-07 (1,18)	-9,31E-07 (-4,0E-01)	-1,97E-05 (-4E-01)	4,10E-01 (5,56E+01)

Impact of $\eta_{2,1}$ on the investments, Case 1

Table 15:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	1,9E-07 (1)	4,2E-07 (4,3E-01)	-1,1E-04 (-1,3)	2,0E-01 (17)	1,9E-07 (1)	4,2E-07 (4,3E-01)	-1,1E-04 (-1,3)	2,0E-01 (17)
Markovian equilibrium	1,4E-07 (5E-01)	1,3E-07 (5,6E-02)	-6,3E-05 (-1,3)	-1,9E-01 (-26)	9,3E-08 (3,3E-01)	2,1E-07 (2E-01)	-6,3E-05 (-1,3)	4,2E-01 (57)

Impact of $\eta_{2,1}$ on the investments, Case 2

Table 16:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	4,06E+01 (5,70E-01)	1,24E+03 (30)	2,32E-02 (5,66E-01)	1,02E-02 (7,28E-01)	1,58E-01 (3,97)	-8,05E-01 (-1,91)	-3,09E-03 (-5E-02)	2,46E-01 (8,6)
Markovian equilibrium	-2,70E+02 (-3,65)	1,26E+03 (21,1)	-6,74E-02 (-1,15)	-4,05E-02 (-1,91)	5,75E-01 (1,42E+01)	-4,44E-01 (-1,23)	1,04E-01 (8E-01)	4,34E-01 (12)

Impact of $\eta_{2,1}$ on different values, Case 1

Table 17:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	2,2E+01 (2,9E-01)	1,3E+03 (4,5E+01)	3,0E-02 (7,2E-01)	1,1E-02 (7E-01)	2,3E-01 (5,8)	-5,0E-01 (-1,2)	6,5E-03 (9,6E-02)	2,9E-01 (10)
Markovian equilibrium	7,3E+01 (8E-01)	1,4E+03 (43)	7,3E-02 (1,1)	3,1E-02 (1,4)	-6,1E-02 (-1,5)	-2,7E-01 (-7,6E-01)	1,7E-02 (2,5E-01)	2,7E-01 (7,3)

Impact of $\eta_{2,1}$ on different values, Case 2

Table 18:

A.3 Impact of the growth in the rich country

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	1,09E-08 (9,09E-01)	4,65E-08 (6,61E-01)	2,61E-08 (1,01)	2,15E-03 (29,6)	1,09E-08 (9,09E-01)	4,65E-08 (6,61E-01)	2,61E-08 (1,01)	-6,15E-04 (-168)
Markovian equilibrium	2,17E-08 (1,04)	9,73E-11 (9,55E-03)	2,62E-08 (9,64E-01)	2,31E-03 (22)	1,14E-08 (6,71E-01)	6,10E-08 (7,7E-01)	2,64E-08 (1,03)	-2,94E-04 (-5,26)

Impact of $\beta_{1,1}$ on the emissions, Case 1

Table 19:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-1,6E-09 (-1,3E-01)	1,0E-07 (1,5)	1,9E-08 (7,3E-01)	2,2E-03 (29)	-1,6E-09 (-1,3E-01)	1,0E-07 (1,5)	1,9E-08 (7,3E-01)	-5,7E-04 (-14)
Markovian equilibrium	5,1E-09 (2,9E-01)	1,1E-07 (1,3)	1,8E-08 (6,9E-01)	2,1E-03 (23)	1,3E-08 (6,3E-01)	1,3E-08 (1,3)	2,3E-08 (8,1E-01)	-6,1E-05 (-9E-01)

Impact of $\beta_{1,1}$ on the emissions, Case 2

Table 20:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,01E-08 (-1,56)	-6,18E-08 (-1,54)	2,3E-06 (7E-01)	-4,94E-04 (-1,1)	-1,01E-08 (-1,56)	-6,18E-08 (-1,54)	2,3E-06 (7E-01)	-4,94E-04 (-1,1)
Markovian equilibrium	-2,03E-08 (-1,84)	6,91E-08 (1,7)	1,4E-06 (7E-01)	-1,03E-03 (-3,58)	1,22E-08 (1,1)	-1,54E-07 (-1,66)	1,4E-06 (7E-01)	4,60E-04 (1,56)

Impact of $\beta_{1,1}$ on the investments, Case 1

Table 21:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	3,8E-09	-4,2E-08	2,6E-06	-4,8E-05	3,8E-09	-4,2E-08	2,6E-06	-4,8E-05
	(5,2E-01)	(-1,1)	(7,6E-01)	(-1E-01)	(5,2E-01)	(-1,1)	(7,6E-01)	(-1E-01)
Markovian equilibrium	1,0E-08	-8,7E-08	1,5E-06	-4,1E-04	-4,1E-09	3,0E-08	1,5E-06	3,9E-04
	(8,9E-01)	(-9,4E-01)	(7,6E-01)	(-1,4)	(-3,7E-01)	(7,1E-01)	(7,6E-01)	(1,3)

Impact of $\beta_{1,1}$ on the investments, Case 2

Table 22:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	9,96E+01 (35)	-1,51E+01 (-9,1)	3,08E-02 (19)	1,56E-02 (28)	-1,32E-03 (-8,3E-01)	8,38E-01 (50)	5,20E-02 (21)	-8,12E-05 (-7,1E-02)
Markovian equilibrium	1,31E+02 (44)	-2,14E+01 (-8,9)	3,70E-02 (16)	1,89E-02 (22)	-7,86E-04 (-4,9E-01)	8,77E-01 (61)	3,94E-02 (7,7)	-3,37E-04 (-2,3E-01)

Impact of $\beta_{1,1}$ on different values, Case 1

Table 23:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	91 (30)	-1,8 (-1,5)	3,5E-02 (21)	1,6E-02 (26)	8,8E-04 (5,7E-01)	8,3E-01 (50)	4,8E-02 (18)	1,5E-03 (1,3)
Markovian equilibrium	90 (25)	-4,0 (-3,1)	3,3E-02 (13)	1,5E-02 (17)	2,2E-03 (1,4)	6,4E-01 (46)	4,6E-02 (17)	3,3E-03 (2,3)

Impact of $\beta_{1,1}$ on different values, Case 2

Table 24:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-2,7E-07 (-9,2E-01)	5,4E-07 (3,1E-01)	-6,5E-08 (-1,0E-01)	9,2E-04 (5,1E-01)	-2,7E-07 (-9,2E-01)	5,4E-07 (3,1E-01)	-6,5E-08 (-1,0E-01)	1,2E-03 (1,4)
Markovian equilibrium	-2,4E-07 (-4,6E-01)	2,5E-07 (1)	-2,4E-08 (-3,5E-02)	8,8E-04 (3,4E-01)	8,4E-08 (2,0E-01)	-3,3E-08 (-1,7E-02)	-6,7E-08 (-1,1E-01)	-8,0E-04 (-5,8E-01)

Impact of $\eta_{1,1}$ on the emissions, Case 1

Table 25:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	3,1E-08 (1E-01)	1,9E-06 (1,1)	6,8E-08 (1E-01)	6,0E-04 (3,1E-01)	3,1E-08 (1E-01)	1,9E-06 (1,1)	6,8E-08 (1E-01)	-3,9E-04 (-3,9E-01)
Markovian equilibrium	-1,6E-07 (-3,5E-01)	2,3E-06 (1,1)	5,7E-08 (8,5E-02)	9,6E-04 (4,2E-01)	1,4E-07 (2,6E-01)	2,0E-07 (8,1E-01)	9,1E-08 (1,3E-01)	-1,0E-03 (-5,9E-01)

Impact of $\eta_{1,1}$ on the emissions, Case 2

Table 26:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	1,4E-07 (8,5E-01)	1,3E-07 (1,4E-01)	7,8E-05 (9,5E-01)	2,1E-01 (19)	1,4E-07 (8,5E-01)	1,3E-07 (1,4E-01)	7,8E-05 (9,5E-01)	2,1E-01 (19)
Markovian equilibrium	2,0E-07 (7,5E-01)	-5,6E-07 (-5,6E-01)	4,5E-05 (9,6E-01)	4,2E-01 (59)	-8,7E-08 (-3,2E-01)	8,1E-07 (3,5E-01)	4,5E-05 (9,6E-01)	-1,8E-01 (-25)

Impact of $\eta_{1,1}$ on the investments, Case 1

Table 27:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	1,9E-07 (1)	-2,6E-07 (-2,7E-01)	8,1E-06 (9,6E-02)	2,0E-01 (18)	1,9E-07 (1)	-2,6E-07 (-2,7E-01)	8,1E-06 (9,6E-02)	2,0E-01 (18)
Markovian equilibrium	2,4E-07 (8,5E-01)	-9,8E-07 (-4,2E-01)	4,7E-06 (9,5E-02)	4,2E-01 (57)	1,8E-08 (6,5E-02)	4,6E-07 (4,4E-01)	4,6E-06 (9,4E-02)	-1,9E-01 (-25)

Impact of $\eta_{1,1}$ on the investments, Case 2

Table 28:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	1,4E+03 (19)	-2,5 (-6,0E-02)	-1,5E-02 (-3,6E-01)	3,8E-03 (2,7E-01)	2,2E-01 (5,7)	-1,2E-01 (-2,9E-01)	8,5E-02 (1,4)	2,9E-01 (10)
Markovian equilibrium	1,5E+03 (20)	83 (1,4)	-9,7E-02 (-1,7)	1,1E-02 (5,3E-01)	-1,7E-01 (-4,2)	7,8E-01 (2,2)	1,7E-01 (1,3)	1,1E-01 (3,1)

Impact of $\eta_{1,1}$ on different values, Case 1

Table 29:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	1,3E+03 (17)	-3 (-1,0E-01)	1,8E-02 (4,3E-01)	-4,1E-04 (-2,6E-02)	2,1E-01 (5,5)	5,5E-01 (1,3)	-9,7E-02 (-1,4)	2,8E-01 (10)
Markovian equilibrium	1,3E+03 (14)	-1,0E+02 (-3,1)	-2,9E-02 (-4,4E-01)	-1,6E-02 (-7E-01)	5,2E-01 (13)	2,1E-01 (6E-01)	-1,6E-01 (-2,3)	2,9E-01 (7,8)

Impact of $\eta_{1,1}$ on different values, Case 2

Table 30:

A.4 Impact of environmental concerns in the rich country

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	1,5E-03 (1,3)	-6,6E-02 (-9,6)	-1,2E-03 (-4,7E-01)	-4 (-5,6E-01)	1,5E-03 (1,3)	-6,6E-02 (-9,6)	-1,2E-03 (-4,7E-01)	-7,3 (-2)
Markovian equilibrium	2,9E-03 (1,4)	-7,2E-02 (-72)	-9,2E-04 (-3,4E-01)	-9,4 (-9,1E-01)	-3,0E-03 (-1,8)	8,1E-03 (1)	-1,7E-03 (-6,9E-01)	9 (1,6)

Impact of α_1 on the emissions, Case 1

Table 31:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	3,0E-03 (24)	-6,1E-02 (-87)	5,6E-04 (2,1)	-12 (-16)	3E-03 (24)	-6,1E-02 (-87)	5,6E-04 (2,1)	-1,1E+01 (-28)
Markovian equilibrium	4,6E-03 (26)	-7,1E-02 (-88)	8,9E-04 (3,3)	-19 (-20)	-1,6E-05 (-7,5E-02)	6,9E-04 (7)	8,3E-05 (2,9E-01)	7,3E-02 (1,1E-01)

Impact of α_1 on the emissions, Case 2

Table 32:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-3,9E-04 (-6,2E-01)	2,2E-02 (5,7)	-3,1E-01 (-9,5E-01)	1,2 (2,7E-02)	-3,9E-04 (-6,2E-01)	2,2E-02 (5,7)	-3,1E-01 (-9,5E-01)	1,2 (2,7E-02)
Markovian equilibrium	-4,4E-03 (-4,1)	6,1E-02 (15)	-1,8E-01 (-9,7E-01)	32 (1,1)	4,1E-03 (3,8)	-3,7E-02 (-4,1)	-1,8E-01 (-9,6E-01)	-31 (-1,1)

Impact of α_1 on the investments, Case 1

Table 33:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,1E-03 (-15)	2,2E-02 (57)	4,4E-02 (1,3)	4,7 (1)	-1,1E-03 (-15)	2,2E-02 (57)	4,4E-02 (1,3)	4,7 (1)
Markovian equilibrium	-4,2E-03 (-36)	5,7E-02 (60)	2,5E-02 (1,3)	16 (5,5)	2,3E-03 (20)	-2,7E-02 (-63)	2,6E-02 (1,3)	-8,3 (-2,8)

Impact of α_1 on the investments, Case 2

Table 34:

A.5 Impact of environmental concerns in the poor country

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-7,7E+06 (-28)	2,2E+05 (1,4)	-990 (-6,2)	-410 (-7,5)	59 (3,8E-01)	-8700 (-5,3)	100 (4,2E-01)	(13) (1,1E-01)
Markovian equilibrium	-7,2E+06 (-25)	5,2E+05 (2,2)	-1300 (-5,6)	-500 (-6)	-100 (-6,6E-01)	-7800 (-5,5)	1100 (2,2)	-1 (-7,3E-03)

Impact of α_1 on different values, Case 1

Table 35:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-7,6E+06 (-250)	-3,3E+04 (-2,8)	-880 (-52)	-430 (-68)	30 (1,9)	-8900 (-53)	-120 (-4,5)	5,4 (4,7E-01)
Markovian equilibrium	-8,5E+06 (-230)	8,4E+04 (63)	-990 (-37)	-490 (-54)	76 (4,7)	-6900 (-49)	-71 (-2,5)	5,2 (3,5E-01)

Impact of α_1 on different values, Case 2

Table 36:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	2,8E-03 (24)	-6,2E-02 (-88)	2,7E-04 (1)	-11 (-15)	2,8E-03 (24)	-6,2E-02 (-88)	2,7E-04 (1)	-11 (-30)
Markovian equilibrium	-3,0E-04 (-1,4)	5,4E-04 (5,3)	-2,4E-04 (-8,7E-01)	1,6 (1,5)	4,5E-03 (26)	-7,1E-02 (-90)	6,1E-04 (2,4)	-18 (-32)

Impact of α_2 on the emissions, Case 1

Table 37:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	3,6E-03 (2,9)	-5,7E-02 (-8,2)	2,6E-03 (1)	-18 (-2,4)	3,6E-03 (2,9)	-5,7E-02 (-8,2)	2,6E-03 (1,0)	-12 (-3,2)
Markovian equilibrium	-2,3E-04 (-1,3E-01)	1,5E-02 (1,9)	1,9E-03 (7,4E-01)	-1,1 (-1,3E-01)	6,3E-03 (3)	-7,1E-02 (-73)	3,2E-03 (1,1)	-24 (-3,5)

Impact of α_2 on the emissions, Case 2

Table 38:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,1E-03 (-17)	2,2E-02 (54)	2,0E-02 (6,1E-01)	9,4E-01 (2,1E-01)	-1,1E-03 (-17)	2,2E-02 (54)	2,0E-02 (6,1E-01)	9,4E-01 (2,1E-01)
Markovian equilibrium	2,3E-03 (21)	-2,6E-02 (-64)	1,2E-02 (6,3E-01)	-1,1E+01 (-3,7)	-4,1E-03 (-37)	5,5E-02 (6)	1,1E-02 (5,7E-01)	1,4E+01 (4,7)

Impact of α_2 on the investments, Case 1

Table 39:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,8E-03 (-2,4)	1,7E-02 (4,3)	-1,6E-01 (-4,9E-01)	-14 (-3,2E-01)	-1,8E-03 (-2,4)	1,7E-02 (4,3)	-1,6E-01 (-4,9E-01)	-14 (-3,2E-01)
Markovian equilibrium	4,3E-03 (3,8)	-4,7E-02 (-5,1)	-9,4E-02 (-4,9E-01)	-25 (-8,7E-01)	-6,1E-03 (-5,5)	6,4E-02 (16)	-9,6E-02 (-5,0E-01)	7,3 (2,5E-01)

Impact of α_2 on the investments, Case 2

Table 40:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-1,8E+06 (-64)	-5,8E+06 (-350)	-910 (-56)	-420 (-76)	6,8E-01 (4,3E-02)	-8600 (-51)	-99 (-4)	-16 (-1,4)
Markovian equilibrium	1,4E+04 (4,9E-01)	-7,1E+06 (-300)	-230 (-9,9)	-88 (-10)	66 (4,1)	490 (3,4)	-22 (-4,4E-01)	-19 (-1,3)

Impact of α_2 on different values, Case 1

Table 41:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-1,2E+06 (-4,2)	-6,2E+06 (-54)	-660 (-4)	-430 (-6,9)	-52 (-3,4E-01)	-8600 (-5,3)	-420 (-1,6)	-36 (-3,3E-01)
Markovian equilibrium	1,2E+06 (3,2)	-7,1E+06 (-55)	-650 (-2,5)	-470 (-5,2)	-14 (-8,8E-02)	-2200 (-1,6)	430 (1,6)	33 (2,3E-01)

Impact of α_2 on different values, Case 2

Table 42:

A.6 Impact of the rate of pollution decay

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-2,0E-02 (-17)	2,0E-01 (29)	-1,5E-03 (-5,9E-01)	77 (11)	-2,0E-02 (-17)	2,0E-01 (29)	-1,5E-03 (-5,9E-01)	76 (21)
Markovian equilibrium	-1,7E-03 (-8,1E-01)	2,0E-02 (20)	-2,9E-04 (-1,1E-01)	4 (3,9E-01)	-2,8E-02 (-17)	2,3E-01 (29)	-2,4E-03 (-9,7E-01)	110 (20)

Impact of δ on the emissions, Case 1

Table 43:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-1,8E-02 (-15)	2,0E-01 (30)	2,2E-03 (8,5E-01)	65 (8,5)	-1,8E-02 (-15)	2E-01 (30)	2,2E-03 (8,5E-01)	73 (19)
Markovian equilibrium	-2,5E-02 (-14)	2,3E-01 (29)	1,3E-03 (5,2E-01)	94 (10)	1,4E-03 (6,7E-01)	2,1E-02 (22)	3,6E-03 (1,3)	-2,8 (-4,1E-01)

Impact of δ on the emissions, Case 2

Table 44:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	6,5E-03 (10)	-7,8E-02 (-20)	4,4E-01 (1,3)	-100 (-2,3)	6,5E-03 (10)	-7,8E-02 (-20)	4,4E-01 (1,3)	-100 (-2,3)
Markovian equilibrium	-1,2E-02 (-11)	8,0E-02 (20)	2,6E-01 (1,3)	12 (4,1E-01)	2,3E-02 (21)	-1,9E-01 (-21)	2,6E-01 (1,4)	-140 (-4,9)

Impact of δ on the investments, Case 1

Table 45:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	7,3E-03 (10)	-7,8E-02 (-20)	2,5E-01 (7,4E-01)	8,5 (1,9E-01)	7,3E-03 (10)	-7,8E-02 (-20)	2,5E-01 (7,4E-01)	8,5 (1,9E-01)
Markovian equilibrium	2,4E-02 (21)	-1,9E-01 (-21)	1,5E-01 (7,5E-01)	-51 (-1,8)	-1,1E-02 (-10)	7,7E-02 (19)	1,4E-01 (7,4E-01)	44 (1,5)

Impact of δ on the investments, Case 2

Table 46:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	8,2E+06 (29)	4,4E+06 (27)	3600 (23)	-4500 (-81)	-89 (-5,7E-01)	1,4E+05 (81)	-2,2E+04 (-89)	-27 (-2,4E-01)
Markovian equilibrium	8,2E+05 (2,8)	7,1E+06 (30)	1200 (5,2)	-6000 (-72)	-390 (-2,4)	1,7E+04 (12)	-2,9E+04 (-57)	-250 (-1,8)

Impact of δ on different values, Case 1

Table 47:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	1,2E+07 (40)	7,7E+05 (6,7)	3500 (21)	-4500 (-73)	-81 (-5,2E-01)	1,3E+05 (82)	-2,2E+04 (-84)	17 (1,6E-01)
Markovian equilibrium	1,3E+07 (37)	3,6E+05 (2,7)	3900 (15)	-4500 (-51)	-200 (-1,2)	1,1E+05 (78)	-2,2E+04 (-79)	8,6 (6,0E-02)

Impact of δ on different values, Case 2

Table 48:

A.7 Impact of the social discount rate

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-2,1E-02 (-52)	9,5E-02 (41)	-2,9E-04 (-3,4E-01)	79 (33)	-2,1E-02 (-52)	9,5E-02 (41)	-2,9E-04 (-3,4E-01)	81 (67)
Markovian equilibrium	-6,6E-03 (-9,6)	1,2E-02 (35)	3,2E-04 (3,6E-01)	33 (9,5)	-1,7E-02 (-31)	1,0E-01 (39)	-7,7E-04 (-9,1E-01)	58 (32)

Impact of ρ on the emissions, Case 1

Table 49:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-2,0E-02 (-49)	9,7E-02 (42)	1,5E-03 (1,6)	78 (30)	-2E-02 (-49)	9,7E-02 (42)	1,5E-03 (1,6)	81 (62)
Markovian equilibrium	-1,6E-02 (-28)	1E-01 (38)	1,0E-03 (1,2)	72 (24)	-5,5E-03 (-7,9)	1,2E-02 (38)	2,0E-03 (2,2)	15 (6,6)

Impact of ρ on the emissions, Case 2

Table 50:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	7,4E-03 (35)	-3,4E-02 (-26)	1,5E-01 (1,4)	-49 (-3,3)	7,4E-03 (35)	-3,4E-02 (-26)	1,5E-01 (1,4)	-49 (-3,3)
Markovian equilibrium	-2,5E-03 (-6,9)	3,3E-02 (25)	1,1E-01 (1,7)	-9,5 (-1)	1,2E-02 (34)	-8,1E-02 (-26)	1,1E-01 (1,8)	-58 (-5,9)

Impact of ρ on the investments, Case 1

Table 51:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	7,3E-03 (30)	-3,6E-02 (-28)	2,7E-01 (2,4)	-63 (-4,1)	7,3E-03 (30)	-3,6E-02 (-28)	2,7E-01 (2,4)	-63 (-4,1)
Markovian equilibrium	1,3E-02 (34)	-8,5E-02 (-28)	1,8E-01 (2,7)	-79 (-8,1)	-2,8E-03 (-7,6)	3,6E-02 (26)	1,8E-01 (2,7)	-5,5 (-5,7E-01)

Impact of ρ on the investments, Case 2

Table 52:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	5,4E+06 (58)	-3E+06 (-55)	2200 (41)	1000 (57)	-7,6 (-1,5E-01)	2,2E+04 (39)	-33 (-4,1E-01)	24 (6,4E-01)
Markovian equilibrium	2,3E+06 (23)	-3,2E+06 (-41)	1000 (13)	470 (17)	-160 (-2,9)	4500 (9,4)	-6E+02 (-3,5)	-3,7E+01 (-7,8E-01)

Impact of ρ on different values, Case 1

Table 53:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	2E+06 (20)	4,3E+05 (11)	2200 (40)	1100 (50)	-22 (-4,2E-01)	2,1E+04 (39)	-36 (-4,1E-01)	15 (4E-01)
Markovian equilibrium	8E+05 (6,7)	8E+05 (18)	2300 (27)	1100 (37)	-140 (-2,6)	1,6E+04 (34)	100 (1,1)	4,6 (9,4E-02)

Impact of ρ on different values, Case 2

Table 54:

A.8 Impact of the investment cost

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-5,8E-08 (-9,8E-03)	-5,2E-05 (-1,5)	-1,0E-06 (-8,0E-02)	2,6E-02 (7,3E-01)	-5,8E-08 (-9,8E-03)	-5,2E-05 (-1,5)	-1,0E-06 (-8,0E-02)	-2,8E-02 (-1,5)
Markovian equilibrium	-8,8E-06 (-8,6E-01)	-8,3E-06 (-1,6)	-1,6E-05 (-1,2)	5,5E-02 (1,1)	-4,4E-06 (-5,3E-01)	-5,2E-05 (-1,3)	3,2E-06 (2,5E-01)	1,3E-03 (4,6E-02)

Impact of γ on the emissions, Case 1

Table 55:

	$\frac{dE_1}{dP}$	$\frac{dE_1}{dM}$	$\frac{dE_1}{dX}$	$cte(E_1)$	$\frac{dE_2}{dP}$	$\frac{dE_2}{dM}$	$\frac{dE_2}{dX}$	$cte(E_2)$
Cooperative equilibrium	-1,8E-06 (-2,9E-01)	5,4E-05 (1,6)	1,7E-05 (1,3)	-1,3E-02 (-3,4E-01)	-1,8E-06 (-2,9E-01)	5,4E-05 (1,6)	1,7E-05 (1,3)	2,6E-02 (1,3)
Markovian equilibrium	-5,2E-06 (-5,9E-01)	6,7E-05 (1,7)	2,1E-05 (1,6)	2,7E-03 (6,0E-02)	4,8E-06 (4,5E-01)	1,2E-06 (2,4E-01)	4,1E-06 (3,0E-01)	-1,6E-03 (-4,6E-02)

Impact of γ on the emissions, Case 2

Table 56:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,6E-04 (-51)	-8,0E-04 (-41)	1,9E-01 (120)	-20 (-88)	-1,6E-04 (-51)	-8,0E-04 (-41)	1,9E-01 (120)	-20 (-88)
Markovian equilibrium	-1,8E-04 (-33)	7,0E-04 (35)	1,1E-01 (120)	-11 (-76)	4,5E-07 (8,3E-02)	-1,7E-03 (-37)	1,1E-01 (120)	-12 (-82)

Impact of γ on the investments, Case 1

Table 57:

	$\frac{dI_1}{dP}$	$\frac{dI_1}{dM}$	$\frac{dI_1}{dX}$	$cte(I_1)$	$\frac{dI_2}{dP}$	$\frac{dI_2}{dM}$	$\frac{dI_2}{dX}$	$cte(I_2)$
Cooperative equilibrium	-1,7E-04 (-46)	-8,6E-04 (-44)	1,9E-01 (120)	-20 (-87)	-1,7E-04 (-46)	-8,6E-04 (-44)	1,9E-01 (120)	-20 (-87)
Markovian equilibrium	1,3E-05 (2,3)	-1,8E-03 (-39)	1,1E-01 (120)	-12 (-79)	-1,9E-04 (-34)	7,6E-04 (36)	1,1E-01 (120)	-11 (-78)

Impact of γ on the investments, Case 2

Table 58:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-810 (-5,8E-01)	-76 (-9,4E-02)	5,7E-01 (7,1E-01)	-2,7E-02 (-9,7E-02)	-7,0E-01 (-9,0E-01)	-1,7 (-2,1E-01)	-3,8E-01 (-3,1E-01)	-3,9E-01 (-7,0E-01)
Markovian equilibrium	1500 (1)	110 (9,2E-02)	1,9 (1,7)	5,6E-01 (1,3)	-2,1 (-2,6)	-7,1 (-9,9E-01)	1,4E-01 (5,7E-02)	-7,8E-01 (-1,1)

Impact of γ on different values, Case 1

Table 59:

	$W_1(10)$	$W_2(10)$	$P(10)$	$M(10)$	$X(10)$	$P(600)$	$M(600)$	$X(600)$
Cooperative equilibrium	-390 (-2,6E-01)	1000 (1,8)	-4,4E-01 (-5,2E-01)	1,6E-01 (5E-01)	1 (1,3)	5,1 (6,2E-01)	1 (7,7E-01)	6,7E-01 (1,2)
Markovian equilibrium	520 (2,9E-01)	1300 (2)	-5,1E-01 (-3,9E-01)	2,8E-01 (6,2E-01)	-5,8E-01 (-7,3E-01)	1,9 (2,7E-01)	4,2E-01 (3,1E-01)	1,5E-01 (2,0E-01)

Impact of γ on different values, Case 2

Table 60:

B Algorithm for the system of coupled algebraic Riccati equations

The algorithm used to compute the solutions of system 4 is taken from Freiling et al. (1996).

1. We compute $K_1^m(0)$ and $K_2^m(0)$ the stabilizing symmetric solutions of the following autonomous algebraic Riccati equations:

$$A'K_1^m + K_1^m A + Q_1 - K_1^m S_1^m K_1^m = 0$$
$$A'K_2^m + K_2^m A + Q_2 - K_2^m S_2^m K_2^m = 0$$

2. We compute the following discrete dynamical system, by taking $K_1^m(0)$ and $K_2^m(0)$ as initial conditions:

$$K_1^m(i+1)\left[A - S_2^m K_2^m(i)\right] + \left[A - S_2^m K_2^m(i)\right]' K_1^m(i+1) + Q_1$$
$$-K_1^m(i+1) S_1^m K_1^m(i+1) = 0$$

$$K_2^m(i+1)\left[A - S_1^m K_1^m(i)\right] + \left[A - S_1^m K_1^m(i)\right]' K_2^m(i+1) + Q_2$$
$$-K_2^m(i+1) S_2^m K_2^m(i+1) = 0$$

   Where i is the number of iterations

3. We stop after i^*, where i^* is such as:

$$\left|K_1^m(i^*)\left[A - S_2^m K_2^m(i^*)\right] + \left[A - S_2^m K_2^m(i^*)\right]' K_1^m(i^*) + Q_1 - K_1^m(i^*) S_1^m K_1^m(i^*)\right|$$
$$+\left|K_2^m(i^*)\left[A - S_1^m K_1^m(i^*)\right] + \left[A - S_1^m K_1^m(i^*)\right]' K_2^m(i^*) + Q_2 - K_2^m(i^*) S_2^m K_2^m(i^*)\right| < \varepsilon$$

   Where ε is a small number, set equal to 10^{-8} in the current simulations.

4. $K_1^m(i^*)$ and $K_2^m(i^*)$ are the solutions of system 4.

Notice that there exist no proof of convergence for this algorithm. However, in the simulations made for this paper, it always converged.

References

Aghion, P., Howitt, P., 1998. Endogenous Growth Theory. MA: MIT Press.

Engwerda, J. C., 2005. LQ Dynamic Optimization and Differential Games. Wiley.

Forster, B., 1975. Optimal pollution control with a nonconstant exponential rate of decay. Journal of Environmental Economics and Management 2, 1–17.

Forster, B., 1977. On a One State Variable Optimal Control Problem, in PITCHFORD J.D. & TURNOVSKY S.J. (eds), Application of Control Theory to Economic Analysis. North Holland Publishing Company, Amsterdam, pp. 229–240.

Freiling, G., Jank, G., Abou-Kandil, H., 1996. On global existence of solutions to coupled matrix riccati equations in closed loop nash games. IEEE Trans. Automatic Conctrol 41, 264–269.

Fudenberg, D., Tirole, J., 1992. Game Theory (second printing).

Golombek, R., Hoel, M., 06 2005. Climate policy under technology spillovers. Environmental & Resource Economics 31 (2), 201–227.

Golombek, R., Hoel, M., 2006. Second-best climate agreements and technology policy. Advances in Economic Analysis & Policy 6 (1), 1472–1472.

Howarth, R., 1996. Discount rates and sustainable development. Ecological Modelling 92, 263–270.

IEA, 2006. Energy Technology Perspectives – Scenarios & Strategies to 2050. The Online Bookstore, IEA.

IPCC, 2007. Climate change 2007: Impacts, adaptation and vulnerability. Tech. rep., IPCC.

List, J. A., Mason, C. F., November 2001. Optimal institutional arrangements for transboundary pollutants in a second-best world: Evidence from a differential game with asymmetric players. Journal of Environmental Economics and Management 42 (3), 277–296.

Romer, P. M., October 1990. Endogenous technological change. Journal of Political Economy 98 (5), 71–102.

van der Ploeg, F., de Zeeuw, A., 1994. "Sustainable growth and renewable resources in the global economy" in Carraro, C. (ed.) Trade, Innovation, Environment. Kluwer, Dordrecht, Ch. 2.3, pp. 229–240.