A Meta-Game Model for Fair Division in Climate Negotiation *

Alain Haurie[†1], Frédéric Babonneau[1,2], Neil Edwards[3], Phil Holden[3], Barbara Pizzileo[3], and Marc Vielle[2]

[1] *ORDECSYS SARL, Switzerland*

[2] *REME, École Polytechnique Fédérale de Lausanne, Switzerland.*

[3] *Environment, Earth and Ecosystems, Open University, Milton Keynes, UK.*

Abstract

This article deals with the problem of fair sharing of a safety cumulative emissions budget up to 2050 where the safety emissions budget is determined chiefly by climate science. Using climate models one may infer the temperature change due to different possible emission pathways provided by world techno-economic models. From these simulations one can identify emissions pathways that keep the temperature increase below threshold levels that should not be overtaken. Now the negotiation could concentrate on the fair sharing of the resulting safety cumulative budget over the time horizon 2010-2050. We assume that an international emissions trading system is the instrument chosen to realize the transfers leading to equity, while retaining efficiency in the abatement activities. We use an integrated assessment model to propose sharings of the safety budget which satisfy some Rawlsian equity criteria when one computes the net welfare effect for the different countries of the optimal supply of quotas corresponding to the relative shares of the emission budget, at different period, on the international emissions trading market. The approach is based on GEMINI-E3, a computable general economic equilibrium model, which is coupled with the climate model of intermediate complexity PLASIM-ENTS. Here the supply of quotas at each period is decided strategically by the regions involved in the negotiations. The equity criterion is

*The research leading to these results has received funding from the EU Seventh Framework Programme (ERMITAGE FP7/2007-2013) under Grant Agreement n^{o}265170.

†Corresponding author: ahaurie@ordecsys.com.

then based on the Nash-equilibrium outcome of the quotas supply game. In conclusion the article compares the results and infers some "robust" recommendations concerning the forthcoming negotiations at the next conferences of the parties.

Keywords. Climate change, International negotiation, Emissions trading, Fair division, Meta-game, Computable general equilibrium model, Game theory.

Contents

1 Introduction and motivation

The issue of fairness in the design of international environmental agreements (IEA) like those that are discussed in the recurrent COP meetings (conference of the parties) must be dealt with efficiently if one wants to create a successful IEA. A community integrated assessment system [31] (CIAS), which brings together different numerical models and climate-related datasets into a common framework can provide interesting insight concerning the possibility to reach a fair IEA that will encourage participation, achieve abatement efficiently and create incentives for compliance. Enhancement and extension of the CIAS concept is one of the main goals of the EU-FP7 research project ERMITAGE http://ermitage.cs.man.ac.uk/.

To characterize a fair IEA we will formulate a multilevel game of fair division of a global "safety budget" of cumulative emissions that remains compatible with a twenty-first century warming that will remain below 2^oC above preindustrial with sufficiently high probability[1]. To reach efficiency and to distribute the benefits of the permit allowances, we assume that an international emissions trading market will be implemented. Finally, we adopt as a criterion of fairness the Rawlsian view that we should minimize the maximum loss of welfare, relative to a business as usual situation. The effect of allowing for non-cooperative behaviour is addressed by comparing the game-theoretic approach with analagous solutions from a partial equilibrium bottom-up modelling framework that utilises a linear programme to derive globally balanced solutions.

In the game-theoretic approach, we suppose that a fair and efficient IEA is reached through the following steps:

First, through international negotiations, several groups of countries, each sharing among its member states a similar level of economic development and exposure to climate risks, agree on: (a) the total level of cumulative GHG emissions allowed over the period 2010-2050, to remain compatible with a 2^oC temperature increase at the end of the twenty-first century; (b) a distribution of this cumulative emission budget among the different groups, for instance using some concepts of equity such as an egalitarian principle à la Rawls [24].

Then, an international emission trading scheme is implemented, with a strategic allocation of allowances to different groups of countries. The different groups of countries play a game of timing, where each group of countries allocates its share of the global allowance over time in order to reach an optimum, if the game is played cooperatively, or an equilibrium, if the game is played non-cooperatively. The payoffs are expressed in terms of variation of surplus with respect to a BAU or reference situation where no climate constraint applies.

To formulate a non-cooperative game of emission quotas supply we extend the model proposed by C. Helm et al. [17, 8, 10] to a framework where the players' payoffs are computed through statistical emulation of a general equilibrium model, GEMINI-E3 [5].

[1]We assume that this corresponds to a 3.75 W/m^2 radiative forcing.

By proposing that the structure of the IEA involves a fixed emissions budget that is shared in a given proportion between states, which can distribute their emissions freely, in a competitive response to market conditions, across a given time horizon, we are recognising the result of Meinshausen and others [20] that, to first order, the level of environmental damage depends on the integrated global emissions up to a given time independent of the time-profile of emissions.

It is beyond the scope of the present article to address the political challenge of negotiating appropriate safety budgets and equity rules. Instead, the focus of the present article is to address the consequences of allowing for non-cooperation between players in their implementation of the envisaged burden-sharing regime, using the most detailed economic and climate modelling practicable to quantify the gains and losses involved. In this way we aim to provide a more realistic basis for addressing the costs and benefits of various burden-sharing possibilities.

In [20] Meinshausen et al. claimed that for a class of emission scenarios, "*both cumulative emissions up to 2050 and emission levels in 2050 are robust indicators of the probability that twenty-first century warming will not exceed 2^{o}C relative to pre-industrial temperatures. Limiting cumulative CO_2 emissions over 2000 - 50 to 1,000 $GtCO_2$ yields a 25% probability of warming exceeding 2^{o}C - and a limit of 1,440 $GtCO_2$ yields a 50% probability - given a representative estimate of the distribution of climate system properties.*[2] This observation has important consequences in the way one can envision international negotiations on climate policy.

However a large uncertainty remains on the safe cumulative emissions limit. Based on recent International Energy Agency scenarios [21, 29] Schaeffer and van Vuuren [26] have proposed new global cumulative emissions budget for 2000-2050 around 1260 $GtCO_2$ (342 GtC), i.e. 26% higher than the estimate made in [20].

In Ref. [12], four institutes of climate research explored different emission pathways that would remain compatible with a global emission budget for 2050 and showed the difficulty to obtain equity in the treatment of developing countries. They noticed, however that a transformation of the world energy system in order to remain compatible with the global cumulative emissions target, is feasible at a cost of less than 2.5 % of GDP. One important insight of the research reported here concerns the possibility to obtain equity through a fair sharing of the cumulative emission budget among different groups of countries, associated with the introduction of an international emissions

[2]Using the conversion factor of 3.67 t CO_2 per t C, the cumulative emissions are 272 GtC and 391 GtC respectively.

trading system with full banking and borrowing [3].

We will also show that the global cumulative emissions constraint approach could be linked with the contraction and convergence proposal, which has attracted considerable attention in recent years (see Ref. [9]):

> *How would "Contraction and Convergence" work? "Contraction" refers to the need to reduce global emissions of greenhouse gases to a level that would result in establishing what science regards as a probably tolerable atmospheric concentration. Effectively this would create a global budget of greenhouse gas emissions. This budget necessarily declines over time until a stable point is reached (as the science improves, our perception of what that point is may change, so any treaty must contain provisions for changing the global budgets). "Convergence' allocates shares in that budget to the emitting nations on the basis of equity. This has three components. First, the budget is global; every country has shares in the atmosphere and any treaty that allocates its absorptive capacity only to a selection of countries effectively deprives the others. Second, the current situation whereby allocations are generally proportional to wealth would cease. Third, allocations should converge over time to a position where entitlements are proportional to population. After convergence, all countries would contract their greenhouse gas emissions equally until the necessary contraction limit is reached. No inflation of national budgets in response to rising populations would be permitted after an agreed set date.*

The paper is an extension of [16]. The paper is organized as follows: in section 2 we review different formulations of noncooperative environmental games and we show how a game with coupled constraint on a global emissions budget can be a robust surrogate to formulations involving unknown damage functions. In section 3 we present the use of a statistical emulation of the climate model PLASIM-ENTS to permit a coupling with techno-economic models and obtain an evaluation of a safe cumulative emissions limit, over the period 2010-2050, compatible with a 2^oC warming in 2100; in section 4 we use GEMINI-E3 scenarios to identify the effect of strategic play of countries in an international emissions trading market with full banking and borrowing; we show how to design a meta-game for the fair sharing of the global cumulative emissions budget.

[3] At the Durban Climate Change Conference - November/December 2011 - the importance of emissions trading and project-based mechanisms in continuation of the Kyoto Protocol. See http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf

Each of the two approaches has its own limits and specific advantages. In section 7 we conclude with a comparison of these results and an interpretation in terms of the possible forthcoming IEA.

2 Multiperiod environmental game models

2.1 A simple multiperiod game

In its most simple formulation the climate change game can be formulated as follows: There are m groups of countries (or players) indexed $j = 1, \ldots, m$, that generate emissions $e_j(t)$ on periods $t \in \{0, 1, \ldots, T\}$. Benefits of emissions are denoted $\pi_j^t(e_j(t))$, with ${\pi_j^t}' > 0$ and ${\pi_j^t}'' < 0$. Associated with the total cumulative emission level

$$E = \sum_{t=0}^{T-1} \sum_{j=1}^{m} e_j(t) \tag{1}$$

are environmental damages $\nu_j(E)$, with $\nu_j'(E) > 0$, $\nu_j''(E) < 0$.

In a Nash equilibrium solution each player tries to maximize its payoff function which corresponds to the discounted sum of benefits minus the damage cost due to GHG accumulation, while taking other countries' choices as given

$$\max_{e_j(\cdot)} z_j = \sum_{t=0}^{T-1} \beta_j^t \pi_j^t(e_j(t) - \nu_j(\sum_{s=0}^{T-1} \sum_{i=1}^{m} e_i(s)). \tag{2}$$

Under appropriate regularity assumptions the first order conditions for a Nash equilibrium are given by Eqs. 3 where the superscript ^{N} refers to the equilibrium value,

$$\beta_j^t {\pi_j^t}'(e_j^N(t)) = \nu_j'(E^N), t = 0, \ldots, T-1; \quad j = 1, \ldots, m. \tag{3}$$

Thus the discounted marginal benefit from emissions for player j is equal to the marginal damage cost at final time T of the cumulative emissions.

In general, climate negotiation will tend to define either a tax scheme or an international emission trading system to induce countries to abate in an efficient way. We will adapt the model to the case where an international emissions trading system is negotiated.

2.2 International emissions trading with strategic allowance choices

In 2003 K. Helm [17] proposed a game model where the strategic variables were the quotas of permits supplied by the players on an international emissions trading market. We recall this model and extend it to a multiperiod setting.

Let $\omega(t) = (\omega_j(t))_{j=1,\ldots,m}$ be the vector of endowment in permits, or quotas, for country j at period t. Let $p^t(\Omega(t))$ be the equilibrium price of permits as a function of the total allowance at time t,

$$\Omega(t) = \sum_{j=1}^{m} \omega_j(t).$$

Each country chooses emissions so as to solve

$$\max_{e_j(\cdot)} w_j = \sum_{t=0}^{T-1} \beta_j^t (\pi_j^t(e_j(t) + p^t(\Omega(t))(\omega_j(t) - e_j(t))$$

The equilibrium conditions of profit maximization and market clearing are

$$\pi_j^{t\prime}(e_j(t)) \quad = \quad p^t(\Omega(t)), \quad t = 0, \ldots, T-1; \quad j = 1, \ldots, m, \tag{4}$$

$$\Omega(t) \quad = \quad \sum_{j=1}^{m} e_j(t), \quad t = 0, \ldots, T-1. \tag{5}$$

This system implicitly defines after-trade equilibrium emissions, $\mathbf{e}_j^t(\Omega(t))$, and the permit price $p^t(\Omega(t))$. Notice here that the permit price at t and the emissions at t for each player j depend uniquely on the total amount of quotas $\Omega(t)$ put on the market at t.

Differentiating (4) and (5) we can express de derivatives taken with respect to $\omega_j(t)$

$$p^{t\prime}(\Omega) \quad = \quad \frac{1}{\sum_{j=1}^{m} \frac{1}{\pi_j^{t}{}^{"}(\mathbf{e}_j^t(\Omega))}} \tag{6}$$

$$\mathbf{e}_j^{t\prime}(\Omega)) \quad = \quad \frac{1}{\sum_{i=1}^{m} \frac{\pi_j^{t}{}^{"}(\mathbf{e}_j^t)}{\pi_i^{t}{}^{"}(\mathbf{e}_i^t)}}. \tag{7}$$

In a climate negotiation each country chooses its permit allowances so as to solve

$$\max_{\omega_j(\cdot)} w_j = \sum_{t=0}^{T-1} \beta_j^t \left(\pi_j^t(\mathbf{e}_j^t(\Omega(t)) + p^t(\Omega(t))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t)))\right) - \nu_j(\sum_{t=0}^{T-1} \Omega(t)).$$

The first order conditions for a Nash equilibrium are given by Eqs 8

$$\begin{aligned} 0 \quad = \quad & \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega(t)))\mathbf{e}_j^{t\prime}(\omega(t))) + p^{t\prime}(\Omega(t))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t)) + p^t(\Omega(t))(1 - \mathbf{e}_j^{t\prime}(\Omega))) \\ & -\nu_j{}'(\sum_{t=0}^{T-1} \Omega(t)) \quad t = 0, \ldots, T-1; \quad j = 1, \ldots, m. \end{aligned} \tag{8}$$

Taking into account that $\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega(t))) = p^t(\Omega(t))$ on a competitive permit market, the conditions (8) can be rewritten

$$\begin{aligned} 0 \quad = \quad & \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega(t))) + p^{t\prime}(\Omega(t)))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t)) - \nu_j{}'(\sum_{t=0}^{T-1} \Omega(t)) \\ & t = 0, \ldots, T-1; \quad j = 1, \ldots, m. \end{aligned} \tag{9}$$

If for each t we sum the m equations (9) and use the identity

$$\sum_{j=1}^{m} \omega_j(t) = \sum_{j=1}^{m} \mathbf{e}_j^t(\Omega(t),$$

we obtain for each t the conditions of Eqs 10

$$0 = \sum_{j=1}^{m} \left(\beta_j^t ({\pi_j^t}'(\mathbf{e}_j^t(\Omega(t))) - {\nu_j}'(\sum_{s=0}^{T-1} \Omega(s)) \right) \quad t = 0, \ldots, T-1. \tag{10}$$

These equations determine the total quotas $\Omega(t)$, at equilibrium, for each t.

We notice the proximity of this model with the classical oligopoly model of industrial organization. There is an implicit demand law for quotas. Each player, through its supply has an influence on the price of quotas and also on the cumulative emissions which determine the damage costs. Each player has a specific abatement and damage cost and must adapt its supply of quotas to the other players behaviour.

There is however an important caveat for the use of these game models. Our ignorance concerning the exact shape of the damage cost functions $\nu_j(\cdot)$ makes these models difficult to use in negotiation assessment. We will see below how the consideration of linear damage cost functions will allow us to link these game models to the class of cost-effectiveness models, where a global constraint on temperature increase in 2100 is imposed in order to avoid serious disruptions of the earth system.

2.3 The case of a linear damage cost

Assume that the damage cost for country j is represented by a linear function $\nu_j(E) = \frac{\nu}{r_j} E$, where $r_j > 0 \quad j = 1 \ldots m$, $\nu > 0$ and $E = \sum_{t=0}^{T-1} \sum_{j=1}^{m} e_j(t)$.

Then the first order equilibrium conditions (9) rewrite as

$$0 = \beta_j^t \left({\pi_j^t}'(\mathbf{e}_j^t(\Omega(t))) + {p^t}'(\Omega(t))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t))) \right) - \frac{\nu}{r_j} \tag{11}$$
$$t = 0, \ldots, T-1; \quad j = 1, \ldots, m.$$

The reader familiar with game theory will notice that these conditions correspond to those characterizing a normalized equilibrium, as defined by Rosen Ref [25] (see also Ref [15]), for a game with payoff

$$\Psi_j(\omega) = \sum_{t=0}^{T-1} \beta_j^t (\pi_j^t(\mathbf{e}_j^t(\Omega(t)) + p^t(\Omega(t))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t)))$$

and coupled constraint

$$\sum_{t=0}^{T-1} \sum_{j=1}^{m} \mathbf{e}_j^t(\Omega(t)) \leq \bar{E}.$$

Then, under appropriate constraint qualification, the scalar ν corresponds to the common Khun-Tucker multiplier associated with the global emission budget $\bar{E}$ and r_j is a weight given to player j in the particular normalized equilibrium selected.

As shown in Ref [3], a normalized equilibrium for the game with coupled constraint

$$\sum_{t=0}^{T-1}\sum_{j=1}^{m}\mathbf{e}_j^t(\Omega(t)) \leq \bar{E}.$$

is also defined by the classical Nash equilibrium for a game with same payoffs

$$\Psi_j(\omega) = \sum_{t=0}^{T-1}\beta_j^t(\pi_j^t(\mathbf{e}_j^t(\Omega(t)) + p^t(\Omega(t))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t)))$$

and decoupled constraint

$$\sum_{t=0}^{T-1}\mathbf{e}_j^t(\Omega(t)) \leq \theta_j\bar{E}, \quad j = 1\ldots m,$$

provided all these constraints remain active at equilibrium. Now the parameter θ_j can be interpreted as the share of the global emission budget which is given to player j as its global quotas for the whole period under consideration.

The Kuhn-Tucker multiplier for player j constraint is denoted μ_j. The following conditions will hold at equilibrium

$$0 = \beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega(t))) + p^{t\prime}(\Omega(t)))(\omega_j(t) - \mathbf{e}_j^t(\Omega(t)) - \mu_j \tag{12}$$

$$t = 0, \ldots, T-1; \quad j = 1, \ldots, m.$$

$$0 = \frac{1}{\theta_j}\sum_{t=0}^{T-1}\mathbf{e}_j^t(\Omega(t)) - \bar{E}. \tag{13}$$

The $\Omega(t)$ are determined by the conditions (10) which write now

$$0 = \sum_{j=1}^{m}\beta_j^t(\pi_j^{t\prime}(\mathbf{e}_j^t(\Omega(t))) - \sum_{j=1}^{m}\frac{\nu}{r_j} \quad t = 0, \ldots, T-1.$$

2.4 The game design problem

We have seen above how the introduction of linear damage cost functions permitted us to reinterpret the game as a cost-effectiveness model, where the players are confronted to a coupled constraint concerning the cumulative amount of emissions or quotas over a given period, the so-called safety emissions budget. We have also seen that the manifold of normalized equilibria in this game with one coupled constraint could be replicated by considering the family of games with decoupled constraints, where each group of countries would be constrained to use a share of the global safety budget.

So the international negotiation could focus on the problem of defining the shares of the safety budget to be given to each group of countries so that the Nash equilibrium solution of the resulting international emissions trading game be as equitable as possible.

3 Statistical emulation of PLASIM-ENTS

One of the principal obstacles to coupling complex climate models to impacts models is their high computational expense. Replacing the climate model with an emulated version of its input-output response function circumvents this problem without compromising the possibility of including feedbacks and non-linear responses [18]. This approach yields two further benefits in the field of integrated assessment. First, the emulation can allow for the construction of gradients of the response function. These may be required, for instance, in an optimisation-based application. Second, a calibrated statistical emulation, based on ensembles of simulations, also provides a quantification of uncertainty and modelling errors.

The climate model we apply here is PLASIM-ENTS, the Planet Simulator [13] coupled to the ENTS land surface model [33]. The resulting model has a 3D dynamic atmosphere, flux-corrected slab ocean and slab sea ice, and dynamic coupled vegetation. We run this model at T21 resolution. As a result of stability issues in the sea ice that have not yet been resolved, all simulations were performed with fixed sea ice. An important consequence is that the modelled climate sensitivity is inevitably reduced, leading to an increased estimate of allowable cumulative emissions in the analysis that follows (i.e. constrained by 2^o global warming).

A 564-member PLASIM-ENTS ensemble was performed varying 22 key model parameters and constrained to generate plausible preindustrial states, following [19]. Each simulation was continued from 1765 to 2105, applying transient historical radiative forcing (1765 to 2005) and a wide range of possible future forcing (2005 to 2105). Globally averaged radiative forcing was expressed as effective CO_2 concentration (CO_2e), together with actual CO_2 concentration (required by the vegetation model). Future radiative forcing has a temporal profile described by a linear decomposition of the 1^{st} three Chebyshev polynomials:

$$CO_{2e} = CO_{0e} + 0.5\{A_{1e}(t+1) + A_{2e}(2t^2-2) + A_{3e}(4t^3-4t)\}$$

where CO_{0e} is CO_2e in 2005 (393 ppm), t is time (2005 to 2105) normalised onto the range (-1,1) and the three coefficients which describe the concentration profile (A_{1e}, A_{2e} and A_{1e}) take values which allow for a wide range of possible future emissions profiles. The same approach was taken to describe the temporal profile of actual CO_2:

$$CO_2 = CO_0 + 0.5\{A_1(t+1) + A_2(2t^2-2) + A_3(4t^3-4t)\}$$

The resulting ensemble of 564 transient simulations of future climate thus incorporates both parametric and forcing uncertainty. We note that the 564 simulations comprise 188 model parameterisations, each reproduced three times and combined with 564 combinations of the six Chebyshev coefficients.

For coupling applications we require an emulator that will generate spatial patterns of climate through time for an arbitrary future forcing, although note that the coupling described here is constrained only by global warming, and hence does not fully utilise this spatio-temporal information. To achieve this, ten decadally averaged output fields (here we consider only surface warming) from 2010 to 2100 were generated for each ensemble member and combined into a single 20480-element vector where, for instance, the first 2,048 elements describe the 64x32 (T21) warming field over the first averaging period. This vector thus represents a self-consistent description of the temporal and spatial dependence of the warming of the respective ensemble member. These vectors were combined into a $20,480 \times 564$ matrix describing the entire ensemble output of warming.

Singular vector decomposition (SVD) was performed on this matrix to decompose the ensemble warming patterns into Empirical Orthogonal Functions (EOFs). The physics of the climate system results in spatio-temporal correlations between ensemble members, patterns of change that are a function of the climate model itself rather than of parameter choices. As a consequence, it is generally the case that a small subset of the 564 EOFs is sufficient to describe most of the variance across the ensemble. The simpler approach of pattern scaling utilises these correlations by assuming that a single pattern (equivalent to the first EOF) can be applied to approximate the pattern from any simulation. Here we retain the first ten EOFs.

Each individual simulated warming field can be approximated as a linear combination of the first ten EOFs, scaled by their respective Principal Components (PCs). As each simulated field is a function of the input parameters, so are the PCs, which are thus scalar quantities that can be emulated as a function of the input parameters. PC emulators of the first ten EOFs were derived as functions of the 22 model parameters and the 6 concentration profile coefficients. The simplest possible emulator was considered here, constructed as a linear function of the 28 inputs.

In order to apply the emulator, we provide the six Chebyshev coefficients that together describe some future concentration pathway of CO_2e and CO_2 as inputs. The emulator generates a 188-member ensemble of the ten PCs (i.e. using each of the 188 parametrisation to make a separate prediction). The ten PCs for each prediction are combined with the ten EOFs to generate patterns of warming over the period (2005-2105). An important aspect of the emulator is its potential to propagate model error through a coupling.

4 An emulation version of GEMINI-E3

In this section we propose a different approach to identify a fair sharing of the safety emissions budget. The sharing itself is obtained as the solution of a game design problem. The game is an adaptation of C. Helm modelling of international emissions trading with endogenous allowance choices [17]. The design parameters are the shares of the safety emissions budget given to the different regions. The use of these shares by the regions is determined by a Nash equilibrium for this game. The rules of the game, i.e. payoffs as functions of strategy choices are obtained from statistical emulations of the general computable equilibrium model GEMINI-E3. This consists in generating a large sample of scenarios corresponding to different strategy choices and identifying through regression analysis the functions describing the regions' costs and benefits that enter into the payoff definition. In fact we should call the resulting model a "meta-game" model defined from statistical emulations of the general computable equilibrium model GEMINI-E3.

In this second approach the fair sharing will be defined according to a Rawlsian principle. We look for the sharing that maximizes the worst ratio of discounted sum of surplus variation over the discounted sum of household consumption in the reference (BAU) case, for the time interval under consideration, 2010-2050.

4.1 Presentation of GEMINI-E3

GEMINI-E3 [6][4] is a multi-country, multi-sector, recursive computable general equilibrium model comparable to the other CGE models (EPPA, ENV-Linkage, etc) built and implemented by other modeling teams and institutions, and sharing the same long experience in the design of this class of economic models. The standard model is based on

[4] All information about the model can be found at http://gemini-e3.epfl.ch, including its complete description.

the assumption of total flexibility in all markets, both macroeconomic markets such as the capital and the exchange markets (with the associated prices being the real rate of interest and the real exchange rate, which are then endogenous), and microeconomic or sector markets (goods, factors of production).

The GEMINI-E3 model is now built on a comprehensive energy-economy dataset, the GTAP-8 database [22]. This database incorporates a consistent representation of energy markets in physical units, social accounting matrices for each individualized country/region, and the whole set of bilateral trade flows. Additional statistical information accrues from OECD national accounts, IEA energy balances and energy prices/taxes and IMF Statistics. We use an aggregated version of GEMINI-E3 that described 11 sectors/goods and 8 regions. Table 1 gives the definition of the classifications used.

Table 1: Dimensions of the GEMINI-E3 model

Regions		Sectors
United States of America	USA	*Energy*
European Union	EUR	01 Coal
Other OECD countries	OEC	02 Crude Oil
China	CHI	03 Natural Gas
India	IND	04 Refined Petroleum
Russia	RUS	05 Electricity
OPEC	OPE	*Non-Energy*
Rest of the World	ROW	06 Agriculture
		07 Energy intensive industries
		08 Other goods and services
		09 Land Transport
		10 Sea Transport
		11 Air Transport

Reference scenarios in CGE models are built from i) forecasts or assumptions on population and economic growth in the various countries/regions, ii) prices of energy in world markets, in particular the oil price and iii) national (energy) policies. We build a reference baseline on the period 2007-2050 with yearly timesteps. Assumptions on population are based on the last forecast done by United Nations [28], we use *the median-fertility* variant. In 2050 the World population will reach 9.27 billions of inhabitants. We use an harmonized set of common economic assumptions that have been defined within the ERMITAGE project and check that our GDP growths are also in line with the last *International Energy Outlook* published by the U.S. Department of Energy [11]. Global GDP growth decreases slightly over the period from 3% annually to 2.5% at the end of our simulation. Prices of energy in the World markets used by GEMINI-E3 are calibrated on those computed by the TIAM-WORLD model used also in the ERMITAGE project.

GHG emissions computed by GEMINI-E3 are presented by regions in Figure 1. These emissions include CO_2 emissions from energy combustion and non-CO_2 greenhouse gases from anthropogenic sources. The non-CO_2 greenhouse gases included in GEMINI-E3 are the direct non-CO_2 GHGs covered by the UNFCCC: methane (CH_4), nitrous oxide (N_2O), and the high global warming potential (high-GWP) gases. In 2050, total GHG emissions reaches 17.4 GtC-eq. The CO_2 emissions profile is in line with RCP 6.0 published recently by [29], these emissions will generate a cumulative emissions budget of 586 GtC-eq over the period 2010-2050.

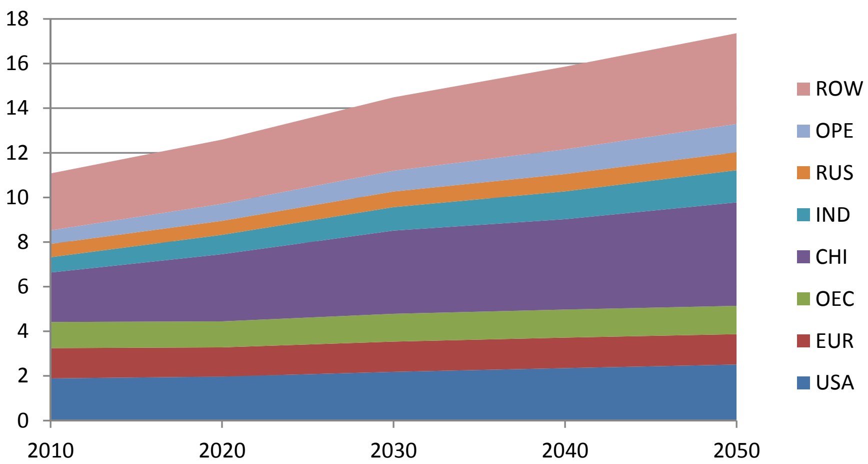

Figure 1: GHG emissions in GtC-eq for the reference case

4.2 Coupling GEMINI-E3 with the emulator of PLASIM-ENTS

The objective of the present coupling is to use the emulator of PLASIM-ENTS to set up emissions constraints into GEMINI-E3 in order to assess climate policy scenarios compatible with a given temperature increase in 2050. As GEMINI-E3 is a time-step optimization model, one can not build a coupled model that would compute endogenously an optimal emissions path with respect to the economy. For this reason, we opt for a soft coupling approach producing acceptable and realistic emission profiles. These emission profiles are then used in GEMINI-E3 as an upper bound vector on the emissions of CO_2 equivalent.

As the number of emissions trajectories satisfying a given warming target is potentially unlimited, the coupling procedure restricts its search to a subset of trajectories. We assume that CO_2 emissions E_{CO_2} have a temporal profile on the range [2000,2050] described by a linear decomposition of the 1^{st} three Chebyshev polynomials:

$$E_{CO_2}(t) = \alpha_1(t+1) + \alpha_2(2t^2-2) + \alpha_3(4t^3-4t), \quad \forall t \in [2000, 2050].$$

To build such functions, the coefficients $\alpha_i,\ i = 1, 2, 3,$ are calibrated on the observed emissions between 2000 and 2010 and on an emission objective in 2050. By changing the latter, one obtains different trajectories that are converted into concentrations to be evaluated by PLASIM-ENTS's emulator. We thus use an interval-halving technique on the emissions target in 2050 to find the emission trajectory satisfying the temperature rise limit.

For the present study, the definition of the safety emission budget for the time period 2010-2050 is crucial as one has to select an appropriate warming target in 2050 that remains compatible with the objective of 2^oC warming in 2100. Here we refer to the RCP2.6 concentration pathway which according to [30] *is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2^oC.* PLASIM-ENTS's emulator computes for this RCP2.6 concentration pathway a warming of 1.45^oC in 2050, so we use this target in our coupling and we derive a safety budget of 424 GtC-eq.

Notice that that all this coupling exercise is used to obtain an evaluation of the safety budget. The emission profile that will be implemented under an international agreement will have to satisfy this global budget. The emissions, for each period, will be determined by the regions using strategically their shares of the safety budget to supply permits on an international emissions trading system, at each period. This game structure is described in the following subsections.

4.3 Statistical analysis of a sample of GEMINI-E3 numerical simulations to define a meta-game of climate negotiations

We apply regression analysis to identify the payoff functions of a game where the strategic variables are the quota supplies by the different regions, at different periods.

The statistical analxsis is based on a sample of 200 numerical simulations of different possible world climate policy scenarios performed with GEMINI-E3. In each scenario, we suppose that a carbon tax is implemented at the world level without emissions trading.

We suppose that all greenhouse gases are taxed including CH_4, N_2O and high-GWP. We compute for each group of countries:

- The abatement level relative to the BAU emissions reported in Figure 1 expressed in million ton of carbon equivalent;
- The welfare cost measured by the households' surplus, and represented by the Compensative Variation of Income (CVI) expressed in US $ [5];
- The Gains or losses from the Terms of Trade (GTT) representing the spill-over effects through change in international prices. In a climate change policy these gains or losses from the terms of trade come mainly from the drop in fossil energy prices due to the decrease of world energy demand. The GTT are expressed in US $.

By subtracting the GTT from the surplus we obtain the Deadweight Loss of Taxation (DWL) i.e. the domestic cost that would occur in a closed economy and which only depends on the abatement done within the country. The GTT represents the imported cost: negative for energy exporting countries such as OPEC and positive for net energy importing countries like Europe and Japan [7]. This imported cost/benefit is function of the world GHG abatement.

Using linear regression techniques, we estimate the abatement cost function (20) (i.e. the parameters $\alpha_j^0(t)$, $\alpha_j^1(t)$, $\alpha_j^2(t)$, $\alpha_j^3(t)$ and $\alpha_j^4(t)$) of player j and period t as a polynomial of degree 4 in the country abatement level. The time periods (t) are 2020, 2030, 2040, 2050 with $n(t)$=10 years for each period. Figure 2 presents the marginal abatement cost (MAC) curves (i.e. the derivative of the abatement cost function with respect to the abatement, see Equation (22)) estimated for the year 2030. It shows where it is the cheapest to abate GHG emissions (Russia, India and China) and where it is the most expensive (EU and ROW).

The gains from the terms of trade of player j is assumed to be an affine function of the global abatement in a given period (see Equation (23)).

5 Formulation of the game design problem, based on GEMINI-E3 statistical emulation

Design variables: θ_j, share of the safety emission budget given to player j.

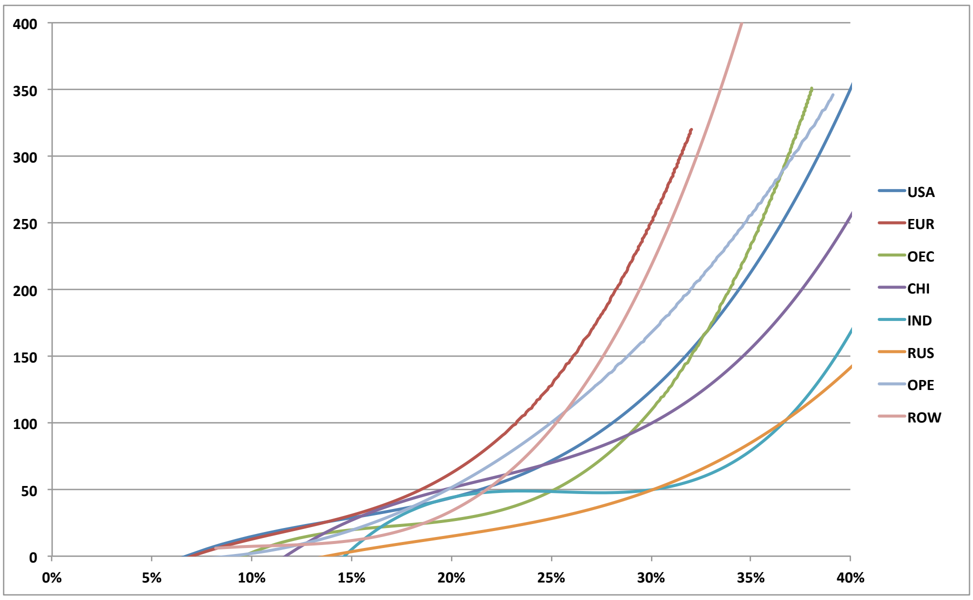

Figure 2: Marginal abatement costs by region in US $ per CO_2 equivalent for the year 2030, proportional abatement

These variables define the key element of the negotiations, namely the sharing of the safety emission budget.

Strategic variables: $\omega_j(t)$, supply of quotas by player j during period t.

We assume that once a player (group of countries) has been given a share of the emission budget, it can supply this amount of quotas (emission rights) on the emissions trading markets organized in the four different decades of the planning horizon. These supplies are strategic variables. They influence the market structure, determining price of carbon, then emission levels by each player, and, finally the transfers (buying and selling of permits) and the net surplus variations.

Secondary (passive) variables: These are variables that will be computed from the values given to the strategic variables. They will be used to describe the permits market functioning. The abatements realized w.r.t. the BAU scenario are the argument of the abatement cost and of the gains from the terms of trade functions that have been identified through regression analysis of a sample of GEMINI-E3 numerical simulations.

$e_j(t)$**:** emission level for player j in period t;

$q_j(t)$**:** abatement level for player j in period t;

$p(t)$**:** carbon price in period t;

$AC_j(t)$**:** abatement cost for player j in period t;

$MAC_j(t)$**:** marginal abatement cost for player j in period t;

$GTT_j(t)$**:** gains from the terms of trade for player j in period t;

ν_j**:** multiplier associated with the share of budget given to player j.

parameters

safety_budget**:** global safety emission budget;

$\mathrm{bce}_j(t)$**:** BAU emissions for player j in period t;

ny(t)**:** number of years in period t;

n(t)**:** number of years in time interval $[1, t]$;

$\alpha_j^0(t)$, $\alpha_j^1(t)$, $\alpha_j^2(t)$, $\alpha_j^3(t)$, $\alpha_j^4(t)$**:** coefficients in the abatement cost function;

$\mu_j^0(t)$, $\mu_j^1(t)$**:** coefficients in the gain from the terms of trade function;

β**:** discount factor;

hc_j**:** discounted household consumption in BAU over the planning horizon.

Payoffs for the game of quotas supply: The players try to minimize the discounted sum of net surplus losses, W, which is the discounted sum of the gains from the terms of trade plus the gains from the permit trading (can be negative) minus the abatement cost, given the actions taken by the other players.

$$W_j(t) = -\sum_t \beta^{\mathrm{n(t)}} \mathrm{ny(t)} \left\{ AC_j(t) - p(t)(\omega_j(t) - e_j(t)) - GTT_j(t) \right\} \tag{14}$$

Notice here that we define the payoffs in terms of surplus gains instead of losses.

Objective of the game design problem: At the upper level where one negotiates the sharing of the safety emissions budget, one may apply a criterion of fairness inspired from the Rawlsian theory of justice:

$$z = \max_\theta \min_j \frac{W_j^\star(t)}{\mathrm{hc}_j}, \tag{15}$$

where $W_j^\star(t)$ is the equilibrium payoff for the game designed by the choice of θ. So we select the sharing which, in the Nash equilibrium solution of the game of quotas supply, maximizes the worst surplus gain among the players.

Constraints and functions: They link the passive variables to the strategic variables, define the cost and profit functions, limit the choices for the strategic variables.

Shares of safety budget: The total supply of quotas by each player is equal to its share of the safety budget:

$$\sum_{\tau} \omega_j(\tau) = \theta_j \, \text{safety\_budget}. \tag{16}$$

Price of carbon equal marginal abatement cost: In a competitive emission permits market, each player will abate at a level where the price of permit equals the marginal abatement cost:

$$p(t) = MAC_j(t), \forall t, j. \tag{17}$$

Permit market clears: In this market, the price is set at such a level that the total emission equals the total supply of quotas:

$$\sum_j \omega_j(t) = \sum_j e_j(t), \forall t. \tag{18}$$

Define emissions from abatements: One must compute abatement level to evaluate abatement costs:

$$e_j(t) + q_j(t) = \mathrm{bce_j(t)}. \tag{19}$$

Abatement cost: The abatement cost is a polynomial of degree 4 in the abatement variable:

$$AC_j(t) = \alpha_j^0(t) + \alpha_j^1(t)\, q_j(t) + \alpha_j^2\, q_j(t)^2 + \alpha_j^3(t)\, q_j(t)^3 + \alpha_j^4(t)\, q_j(t)^4. \tag{20}$$

Marginal abatement cost: The marginal abatement cost is obtained through derivation of the abatement cost:

$$MAC_j(t) = \alpha_j^1(t) + 2\,\alpha_j^2(t)\, q_j(t) + 3\,\alpha_j^3(t)\, q_j(t)^2 + 4\,\alpha_j^4(t)\, q_j(t)^3. \tag{21}$$

Derivative of marginal abatement cost: One also needs to compute the derivative of the marginal cost function:

$$DMAC_j(t) = 2\,\alpha_j^2(t) + 6\,\alpha_j^3(t)\, q_j(t) + 12\,\alpha_j^4(t)\, q_j(t)^2. \tag{22}$$

Gains from the terms of trade: The gains from the term of trade are expressed as a linear function of the sum of the abatements decided by all the players:

$$GTT_j(t) = \mu_j^0(t) + \mu_j^1(t) \sum_i q_i(t). \tag{23}$$

Derivative of carbon price: One has to compute the derivative of the carbon price w.r.t. any supply $\omega(t)$ which is given by (see [17]):

$$DP(t) = \frac{-1}{\sum_j \frac{1}{DMAC_j(t)}}. \tag{24}$$

Pseudo-gradient of payoffs: We can now write pseudo-gradient of the payoffs w.r.t. the strategic variables

$$PSGRAD_j(t) = -\beta^{\mathrm{n(t)}}\mathrm{ny(t)}\left\{MAC_j(t) - DP(t)\left(\omega_j(t) - e_j(t)\right) - \mu_j^1(t)\right\} + \nu_j. \tag{25}$$

The first order conditions for a Nash equilibrium are then

$$\begin{aligned}
\nu_j &\geq 0 \\
\theta_j \,\text{safety_budget} - \sum_\tau \omega_j(\tau) &\geq 0 \\
\nu_j \,\theta_j \,\text{safety_budget} - \sum_\tau \omega_j(\tau) &= 0 \\
&\quad \forall j \\
-PSGRAD_j(t) &\geq 0 \\
\omega_j(t) &\geq 0 \\
\omega_j(t)\, PSGRAD_j(t) &= 0 \\
&\quad \forall j, \forall t.
\end{aligned}$$

6 A solution to the game design problem

We use a safety budget equal to 424 GtC-eq as defined in section 4.2, the discount factor β is 3% per year. We simulate options that have been proposed for designing a global agreement on climate change [4]. The first one is based on an egalitarian rule that supposes that each individual has the right to emit an equal amount of greenhouse gases, in our case the budget share is proportional to the population over the period 2010-2050. The second rule considers that the allocation of quotas is proportional to emissions in the BAU simulation. This sovereignty principle is usually proposed as a starting point in environmental negotiations taking into account the existing situations. Finally we also present a solution corresponding to the max min of the surplus losses expressed in % of BAU consumption, computed from a sample of simulations that we have tested[5].

[5] We test the local stability of this equilibrium (called $\theta_j^\star$) by varying the θ_j around this equilibrium. We simulate all the solutions in the range [$\theta_j^\star$-0.02; $\theta_j^\star$+0.02] with a step of 0.01. It gives 5^7 (78125) runs with $\theta_{row} = 1 - \sum \theta_i$.

In this solution the maximum loss, among the eight groups of countries, expressed as a percentage of the discounted total consumption in the BAU case, is minimal. This max min solution tends to equalize welfare costs as a percentage of GDP.

Experience shows that negotiators do not put forward a single allocation rule based on a clearly identified value judgment on equity but a mix that takes into account their own features and situation. Table 2 gives the different distributions of the total budget that have been tested.

Table 2: Different sharings tested (θ_j)

	USA	EUR	OEC	CHI	IND	RUS	OPE	ROW
Egalitarian rule	0.04	0.06	0.06	0.17	0.18	0.02	0.07	0.40
Sovereignty rule	0.15	0.09	0.09	0.25	0.07	0.05	0.07	0.23
max min solution	0.15	0.07	0.075	0.25	0.07	0.05	0.085	0.25

In each case we have computed the Nash equilibrium for the game of quota supply defined above and we have obtained the following evaluations of the surplus loss, expressed as a percentage of discounted total consumption over the 2010-2050 period. The results are shown in Table 3. The equalitarian rule gives a large number of extreme welfare impacts, where Russia, China and USA would support a very high burden whereas the ROW and India would largely benefit from climate protection. In contrary the sovereignty rule would have a more concentrated range of welfare costs, but would impose a high burden on OPEC and ROW.

Table 3: Corresponding surplus losses (% of BAU discounted household consumption)

	USA	EUR	OEC	CHI	IND	RUS	OPE	ROW	Max loss
Egalitarian rule	4.81	1.64	2.02	10.63	-34.51	13.65	3.97	-7.74	13.65
Sovereignty rule	0.79	0.33	0.18	0.64	0.87	0.26	4.51	1.70	4.51
max min solution	0.78	0.87	0.86	0.75	0.93	0.33	0.23	0.62	0.93

6.1 Equilibrium for the max min allocation

We examine the equilibrium solution corresponding to the sharing of the safety budget shown in Table 4.

It is interesting to compare this budget allocation with the emissions reduction target defined by the countries. The EU climate change policy aims to reducing by 20% in 2020 and 75% in 2050 the GHG emissions from the 1990 levels, this gives a budget equal to 35 GtC-eq for the next 40 years. This budget is 17% higher than the one computed

Table 4: Allocation and equilibrium solution expressed in surplus loss ratios

Countries	GtC-eq	% safety budget
USA	63.6	15.0%
EUR	29.7	7.0%
OEC	31.8	7.5%
CHI	106.0	25.0%
IND	29.7	7.0%
RUS	21.2	5.0%
OPE	36.4	8.5%
ROW	106.0	25.0%
World	424.0	100.0

in our equilibrium. The US climate targets is more uncertain in the long term. At the Cancún UN climate summit in December 2010 the U.S. delegation confirmed the target of reducing GHG emissions by 17% in 2020 compared to 2005 levels. But nothing was enacted concerning long term target like 2050. In Ref.[23] the authors developed three paths of emissions control spanning the range of Congressional proposals, the cumulative allowance allocations between 2012 and 2050 of the policy are 78.4, 55.5 and 45.6 GtC. The three climate policies are based on allowance allocations that through 2050 are: 1) constant at 2008 emissions levels, 2) linearly reduced to 50% below 2008 levels, 3) linearly reduce emissions to 80% below 2008 levels. Our allocation for USA is close the -50% target even if our budget is 8 GtC-eq more generous. Concerning developing countries, we can translate their cumulative emissions budget in a target for the year 2050 that would be required to reach if we suppose that this climate target is achieved through a linear decrease of GHG emissions. We compute the target in comparison with the 2010 emissions levels. These objective are for China, India, Russia, OPEC and ROW respectively +38%, +17%, -16%, +155% and +18%. Our target for China gives in 2020 a reduction in Chinese GHG intensity (i.e. GHG emissions divided by GDP) in 2020 with respect to 2007 levels by -52% which is in line with the target defined by the Chinese government. In 2009, the Chinese government committed to cut its CO_2 emissions per unit of GDP by 40-45% of the 2005 levels by 2020 [34]. The allocation given to OPEC is necessary to compensate the loss of energy exporting revenue and is close to the cumulative BAU emissions that are equal to 40 GtC-eq.

The prices of permits are shown in Table 6.

Figure 3 below shows how the distribution of quota supplies by each group of countries changes over the periods. One notices a relative stability of these ratios.

Comparing quotas and emissions we obtain the yearly transfers of emission rights

Table 5: Quotas supplied by countries at each decade in GtC-eq

	2011-2020	2021-2030	2031-2040	2041-2050	2011-2050
USA	14.7	15.6	16.3	17.0	63.6
EUR	7.9	7.7	7.3	6.8	29.7
OEC	8.1	8.1	7.9	7.8	31.8
CHI	21.5	26.0	27.8	30.7	106.0
IND	6.0	6.9	7.9	8.8	29.7
RUS	4.7	5.1	5.6	5.8	21.2
OPE	6.9	8.3	9.8	11.1	36.0
ROW	22.6	25.0	28.0	30.4	106.0
Total decade	92.6	102.6	110.5	118.4	424.0

Table 6: CO_2 price in US$ per ton of CO_2-equivalent

2020	61
2030	81
2040	108
2050	145

(positive means Sale, negative means Buy) shown in Table 7, OECD countries (USA, EUR and OEC) are net buyers of permits, in contrary emerging and developing countries sale quotas. The main buyers of permits is the European Union whose GHG abatement costs are high. Concerning the sellers side, China and OPEC are the main actors. China benefits from large possibilities of reduction associated with limited abatement costs and OPEC can sell its generous allocations that have been given to overcompensate the losses of energy exporting revenue.

Table 7: Net selling (+) or buying (-) of quotas by countries at each decade in GtC-eq

	2011-2020	2021-2030	2031-2040	2041-2050	2011-2050
USA	-0.58	-0.53	-0.59	-0.69	-2.39
EUR	-2.84	-2.98	-3.26	-3.56	-12.64
OEC	-0.94	-0.96	-1.02	-1.12	-4.04
CHI	2.25	1.92	1.85	1.93	7.94
IND	0.47	0.52	0.55	0.58	2.12
RUS	0.36	0.45	0.55	0.63	1.98
OPE	0.92	1.16	1.43	1.66	5.17
ROW	0.36	0.43	0.50	0.57	1.85
World	0.00	0.00	0.00	0.00	0.00

The costs borne by regions presented in Table 3 can be decomposed in three components 1) the domestic cost of abatement, 2) the gains or losses coming from the terms of

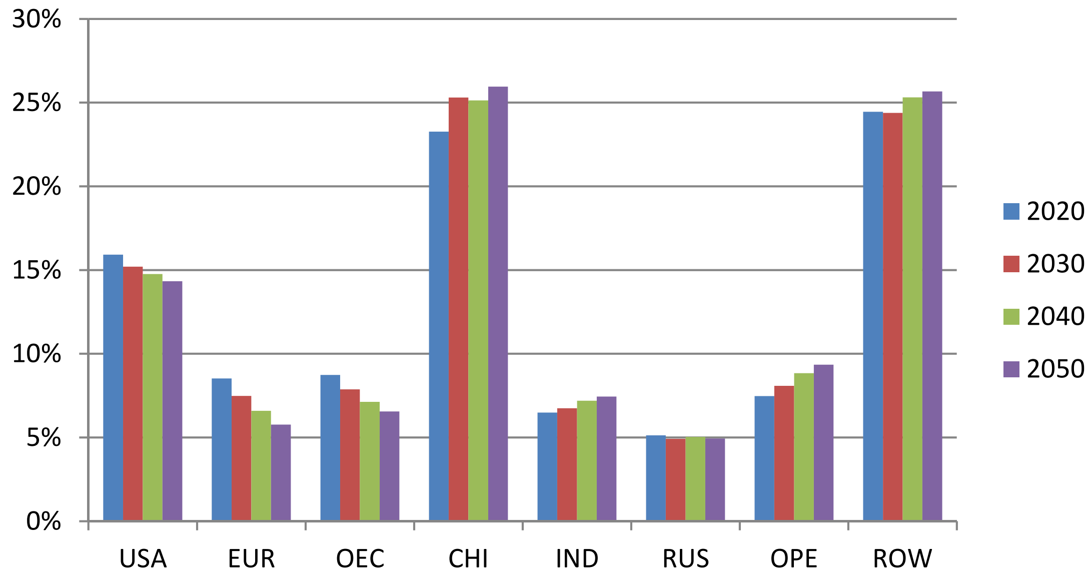

Figure 3: Quotas supplied by countries in % at each decade

trade (i.e. the imported cost/gain), 3) the buying or selling of permits. This decomposition is displayed in Figure 4, it shows that for India and Russia large positive transfers of permits are required to compensate the abatement cost of GHG. In the case of OPEC the selling of permits allows also a reduction of the important losses of energy export revenues. China is the only region where the gains from terms of trade represent an important share in the aggregated cost. In industrialized regions the trade of permits represents a cost. This cost is significant for European Union and Other OECD regions. In contrary, the buying of quotas represents a small share of the total cost borne by USA.

7 Conclusion

In this study we have used an approach to evaluate a possible fair sharing of the burden of keeping climate change inside a tolerable region. The outcome of negotiation is assumed to be reduced to the definition of a fair sharing of a safety emission budget. To evaluate this budget we have used first an emulator of a complex climate model, PLASIM-ENTS coupled with top-down general equilibrium model GEMINI-E3. Using this model we

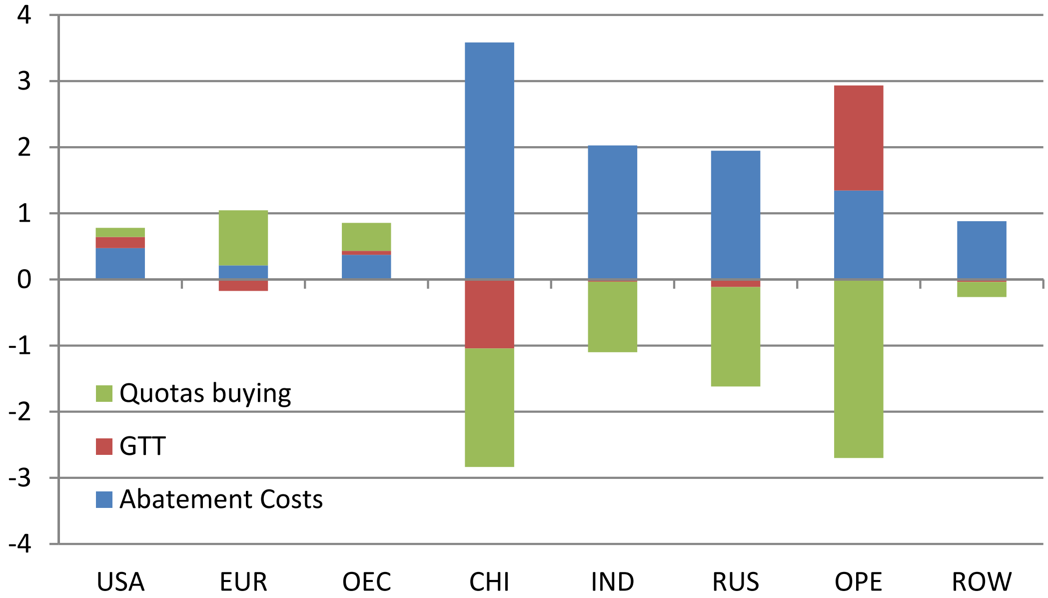

Figure 4: Decomposition of the surplus losses in % of BAU discounted household consumption

have defined a way to assess the net benefit expressed in terms of a ratio of surplus over household consumption. The surplus is computed after the establishment of an "optimal international emissions trading market". Then we were able to find the sharing of the safety emissions budget that would maximize the minimum of these ratios. We used statistical analysis of a sample of numerical simulations performed with GEMINI-E3 to define the payoff functions of the players/regions in a non-cooperative game of strategic allocation of their shares of the safety emission budget, as quotas for each period in the international emissions trading system. This second way of organizing the market has the advantage of avoiding the (restrictive) assumption that a benevolent planner determines the allocation of quotas for each player at each period; it should therefore be more acceptable in the negotiation process.

Doing this analysis with a CGE model coupled with an emulator of an advanced moderate complexity climate model we made the following observations that could be important for the forthcoming climate negotiations:

(i) The mid-term (2010-2050) costs of the climate abatement strategies to keep the long term temperature increase below 2^oC remain moderate: at the worldwide level, the cumulative discounted abatement cost in percentage of cumulative and discounted GDP is equal to 0.46%. this approach shows that to reach the 2^oC target as defined by EU seems feasible with reasonable economic costs over the time horizon 2050. It is important to remember that these costs, over 2010-2050, represent only one part of the total abatement costs needed to respect the 2^oC target. Indeed, abatement must be pursued after 2050, with corresponding costs to be considered.

(ii) A crucial issue is to identify the distribution of the burden that equalizes and limits high costs of implementation; we have shown that the models currently available can provide some valuable insights when they are associated with some optimization or game design meta-models. We also demonstrate that the implementation of a global market of tradable permits is a relevant economic instrument that could help to achieve the burden sharing. The first steps of the The EU Emissions Trading System and its extension to new partners could be the presages of a worldwide trading scheme.

(iii) Concerning the regional burden sharing the following conclusions are found: (a) OECD countries are net buyers of permits and the contributions computed by our models are close to the existing commitments or propositions made by OECD countries; (b) Emerging and developing countries are net sellers; they will be helped by the organization of international emissions trading systems, on which they can play strategically with their shares of the safety emissions budget; (c) China is an essential player as it received more than 25% of the budget in all cases.

(iv) The agreements analyzed in this paper considered a limited number of players, compared to the 197 countries involved in the UNFCCC negotiations. The need to define a more limited forum to discuss the type of agreement architecture proposed in this paper might deserve some more attention. The Group of Twenty (G20) might be a possibility: in 2010, the G20 members represent 76% of global GHG emissions and almost 90% of global GDP.

Finally, our analysis demonstrates the potential for using statistical emulation and meta-modelling techniques to derive more realistic representations of the potential costs and benefits associated with various possible international environmental agreements, including the effects of non-cooperative behaviour of agents. The construction of statistical emulators from large ensembles of model simulations to cover a wider range of possibilities, and comparison between models of different structures, can play an essential role in assessing the multitude of related uncertainties. Further work is needed in this area to identify the most robust forms of agreements.

References

[1] Arnell N. W. , J. A. Lowe, S. Brown, S. N. Gosling, P. Gottschalk, J. Hinkel, B. Lloyd-Hughes, R. J. Nicholls, T. J. Osborn, T. M. Osborne, G. A. Rose, P. Smith and R. F. Warren. A global assessment of the effects of climate policy on the impacts of climate change, Nature Climate Change, 2013.

[2] Arrhenius S. On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science (fifth series), 41:237275, April 1896.

[3] Bahn O. and A. Haurie, A Class of Games with Coupled Constraints to Model International GHG Emission Agreements. International Game Theory Review, 10(4)337-362, 2008. 9

[4] Baumert K.A., O. Blanchard, S. Llosa, and J.F. Perkaus (Ed.). Building on the Kyoto Protocol: Options for Protecting the Climate, World Resources Institute, Washington D.C., 2002. 20

[5] Bernard A. and M. Vielle. Measuring the Welfare Cost of Climate Change Policies: A Comparative Assessment Based on the Computable General Equilibrium Model GEMINI-E3, Environmental Modeling & Assessment, 8:199-217, 2003. 3, 16

[6] Bernard A. and M. Vielle. GEMINI-E3, a General Equilibrium Model of International National Interactions between Economy, Energy and the Environment, Computational Management Science, 5:173-206, 2008. 12

[7] Böhringer C. and T. F. Rutherford. Carbon abatement and international spillovers, Environmental and Resource Economics, 22:391-417, 2002. 16

[8] Böhringer C. and C. Helm. On the fair division of greenhouse gas abatement cost, Resource and Energy Economics, 30(2):260-276, 2008. 3

[9] Broad J. Contraction and Convergence, Ecologist, 29(2):141, March / April 1999. 5

[10] Carbone J. C., C. Helm, and T. F. Rutherford. The case for international emission trade in the absence of cooperative climate policy, Journal of Environmental Economics and Management, 58(3):266-280, 2009. 3

[11] Energy Information Administration, International Energy Outlook U.S., Department of Energy, 2011 13

[12] England M., S. Kartha, C.K. Siebert, R. Mathur, J. McCarthy, D. Messner, N. Nakicenovic, V. Ramanathan, J. Rockstrm, J. Schellnhuber and L. Srivastava. A Copenhagen Prognosis: Towards a Safe Climate Future. Technical report, 2010. 4

[13] Fraedrich K., Jansen H., Kirk E., Luksch U. and Lunkeit F.: The Planet Simulator: Towards a user friendly model, Meteorologische Zeitschrift, 14:299-304, 2005. doi: http://dx.doi.org/10.1127/0941-2948/2005/0043 10

[14] GLOBE International 2013, Climate Legislation Study: A Review of Climate Change Legislation in 33 Countries. Third Edition. Eds. Terry Townshend, Sam Fankhauser, Rafael Aybar, Murray Collins, Tucker Landesman, Michal Nachmany and Carolina Pavese.

[15] Haurie A. , J,B. Krawczyk, G. Zaccour, Games and Dynamic Games, Now-World Scientific, 2012. 8

[16] Haurie A., F. Babonneau, N. Edwards, P. Holden, A. Kanudia, M. Labriet, B. Pizzileo, M. Vielle, Fairness in Climate Negotiations: a Meta-Game Analysis Based on Community Integrated Assessment in Willi Semmler and Lucas Bernard, eds. The [Oxford] Handbook of the Macroeconomics of Climate Change. to appear 2013. 5

[17] Helm C. International emissions trading with endogenous allowance choices, Journal of Public Economics, 87(12):2737-2747, 2003. 3, 6, 12, 20

[18] Holden PB and Edwards NR. Dimensionally reduced emulation of an AOGCM for application to integrated assessment modelling, Geophysical Research Letters, L21707, 2010. doi:10.1029/2010GL045137 10

[19] Holden PB, Edwards NR, Oliver KIC, Lenton TM and Wilkinson RD. A probabilistic calibration of climate sensitivity and terrestrial carbon change in GENIE-1, Climate Dynamics, 35:785-806, 2010. doi: 10.1007/s00382-009-0630-8. 10

[20] Malte Meinshausen, Nicolai Meinshausen, William Hare, Sarah C. B. Raper, Katja Frieler, Reto Knutti, David J. Frame, & Myles R. Allen, Greenhouse-gas emission targets for limiting global warming to 2^oC. Nature, 458:1158-1163, 2009. 4

[21] Moss R.H., Edmonds J.A., Hibbard K.A., Manning M.R., Rose S.K., van Vuuren D.P., Carter T.R., Emori S., Kainuma M., Kram T., et al. The next generation of scenarios for climate change research and assessment. Nature, 463:747-756, 2010. 4

[22] Narayanan B., A. Aguiar, R. McDougall (Eds.). Global Trade, Assistance, and Production: The GTAP 8 Data Base, Center for Global Trade Analysis, Purdue University, 2012. 13

[23] Paltsev S., J. M. Reilly, H. D. Jacoby, J. F. Morris. The cost of climate policy in the United States, Energy Economics, 31(2):S235 - S243, 2009. 22

[24] Rawls J., A Theory of Justice. Harvard University Press, 1971 - 623 pages. 3

[25] Rosen J.B. Existence and uniqueness of equilibrium points for concave n-person games, econometrica, Vol. 33, No 3, pp. 520-534, 1965. 8

[26] Schaeffer M. and D. van Vuuren. Evaluation of IEA ETP 2012 emission scenarios. Climate Analytics Working Paper 201281. Karl-Liebknecht-Strasse 5, 10178 Berlin, Germany, May 2012. 4

[27] Stern N. , The Economics of Climate Change, The Stern Review, Cambridge University Press, 712 pp, 2007.

[28] United Nations, Department of Economic and Social Affairs, Population Division, World Population Prospects: The 2010 Revision, 2011. 13

[29] van Vuuren D. P., J. Edmonds, M. Kainuma, K. Riahi A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, N. S. J. Smith, S. K. Rose. The representative concentration pathways: an overview, Climatic Change, 109:5-31, 2011. 4, 14

[30] van Vuuren, D.P. , Stehfest, E., den Elzen, M.G.J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., Oostenrijk, R., van Ruijven, B. RCP2.6: exploring the possibility to keep global mean temperature increase below 2^oC, Climatic Change, 109(1-2):95-116, 2011. 15

[31] Warren R. , S. de la Nava Santos, N.W. Arnell, M. Bane, T. Barker, C. Barton, R. Ford, H.-M. Fuessel, Robin K.S. Hankin, J. Hinkel, Rupert Klein, C. Linstead, J. Kohler, T.D. Mitchell, T.J. Osborn, H. Pan, S.C.B. Raper, G. Riley, H.J. Schellnhueber, S. Winne, D. Anderson. Development and illustrative outputs of the Community Integrated Assessment System (CIAS), a multi-institutional modular integrated assessment approach for modelling climate change, Environ. Model. Software 23(5):592-610, 2008. 2

[32] Watkiss P. (Ed) 2011, The ClimateCost Project, Final Report, Volume 1: Europe, Stockholm Environment Institute, Sweden, 2011.

[33] Williamson MS, Lenton TM, Shepherd JG and Edwards NR. An efficient numerical terrestrial scheme (ENTS) for Earth system modelling, Ecological Modelling, 198:362-374, 2006. 10

[34] Yi W.-J. , L.-L. Zou, J. Guo, K. Wang, and Y.-M. Wei. How can China reach its CO_2 intensity reduction targets by 2020? A regional allocation based on equity and development, Energy Policy, 39:2407-2415, 2011. 22