Environmental Modeling & Assessment
https://doi.org/10.1007/s10666-018-9630-6

Meta-Modeling to Assess the Possible Future of Paris Agreement

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Received: 14 November 2017 / Accepted: 12 July 2018

Abstract

In the meta-modeling approach, one builds a numerically tractable dynamic optimization or game model in which the parameters are identified through statistical emulation of a detailed large scale numerical simulation model. In this paper, we show how this approach can be used to assess the economic impacts of possible climate policies compatible with the Paris Agreement. One indicates why it is appropriate to assume that an international carbon market, with emission rights given to different groups of countries will exist. One discusses the approach to evaluate correctly abatement costs and welfare losses incurred by different groups of countries when implementing climate policies. Finally, using a recently proposed meta-model of game with a coupled constraint on a cumulative CO_2 emissions budget, we assess several new scenarios for possible fair burden sharing in climate policies compatible with the Paris Agreement.

Keywords COP21 · Climate policy · Meta-modeling · Game with coupled constraints · International emissions trading scheme · Computable general equilibrium model · Rawlsian equity rule

1 Introduction

The aim of this paper is to show how one can assess the economic impacts of the possible international agreements on climate policy that will follow the Paris Agreement by using "meta-models" that are built from statistical emulation of a world computable general equilibrium (CGE) model. Doing so, we extend and further develop a recently published analysis [1] in three ways: (i) we show why it is appropriate to assume that an international carbon market with emissions rights allocated to countries will exist in the future to implement climate policy, (ii) we detail the macroeconomic reasoning behind the assessment with a CGE of the relevant abatement costs and welfare losses for different groups of countries and, (iii) we explore a benchmark scenario compatible with the 2°C target and we compare it with scenarios based on a game meta-model already presented in [1–4]. In all these scenarios, we address the fair burden sharing issue by defining an allocation of the cumulative CO_2 emissions budget, which tends to equalize the relative welfare losses among eight (8) groups of countries.

The Paris Agreement main result was a commitment by more than 160 nations to limit to less than 2°C (and possibly 1.5°C) the temperature rise due to greenhouse gas (GHG) emissions. As a first step to achieve this goal, intended nationally defined contributions or INDCs have been announced in a bottom-up approach. These INDCs will not produce the necessary abatements. Therefore, they should be followed by more stringent abatement decisions, leading to a situation of net zero emissions [5] at the end of the century. The recent announcement by the American administration that it is pulling out of the agreement adds uncertainty on how these necessary abatements will be made and how the burden sharing issue will be addressed among the different groups of countries that are exposed to the danger of climate change. On the other hand, there is now a scientific consensus concerning a global safety cumulative CO_2 emissions budget that should not be exceeded over the rest of the twenty-first century in order to reach the 2°C target with sufficiently high probability. This budget has been evaluated around 1800 Gt CO_2 in recent climate modeling work [6, 7].

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The forthcoming negotiations will be complex involving macroeconomic evaluation, monitoring, technological assessment and transfers, development aid for emerging economies etc [7]. To perform the economic assessment of possible climate policies, one can use an Integrated Assessment Model (IAM) such as, to cite a few, DICE [8], MERGE [9], TIAM [10], and BaHaMa [11, 12]. Another approach, which will be adopted in this work, is based on the use of world CGE models such as GEMINI-E3, the model to be used in this paper; EPPA [13, 14]; GEM-E3 [15–17]; and IMACLIM-R [18]; these are a few examples of CGE models used by research groups in the USA or Europe working on the economics of climate change.

Through numerical simulations these models permit an evaluation of different possible economic instruments, like, e.g., carbon tax vs. cap and trade schemes and provide economically coherent evaluations of the welfare losses incurred by different countries when implementing a particular agreement. To represent the agreements that should result from climate negotiations and to identify among the possible agreements those which pass a fairness test, we propose to rely on a meta-modeling approach. A meta-model will be a dynamic game model in which the players are groups of countries (coalitions), the strategies are supply schedules of emissions permits on an international carbon market and the payoffs are welfare gains (or losses). The payoffs depend crucially on the abatement costs and gains from changes in the terms of trade, which can be evaluated, for each coalition, through numerical simulations performed with the world CGE model, GEMINI-E3. Similar meta-modeling approaches have already been used to assess the "hot air" situation arising in the Kyoto Protocol, due to the allocation of permits to Russia on the basis of Soviet Union era emission levels ([19, 20]). Another meta-model has been used to represent the strategic allocation of emission allowances in the EU [21], and more recently, the method has been proposed as a way to address the delicate issue of fair burden sharing in climate negotiations ([2–4]). The fair burden-sharing issue concerns the definition of an agreement framework permitting an equitable distribution of the relative charges for the different parties.

In summary, the meta-models used for the assessment and design of fair and efficient agreements rely on (i) the definition of a global emissions budget compatible with the 2°C target to be shared among the nations through negotiations; (ii) the implementation of an international carbon market; and (iii) the strategic noncooperative or cooperative use of emissions permits on the international market by the groups of countries striving to minimize their welfare losses.

The rest of the paper is organized as follows: in Section 2, one vindicates the representation of an international emissions trading scheme as a market where coalitions of countries are the main actors and one shows how GEMINI-E3 can provide an evaluation of the abatement costs and welfare losses due to climate policy for different groups of countries; in Section 3, the costs and welfare losses for the INDCs and a benchmark scenario are discussed; in Section 4, one introduces the meta-modeling approach which is then used to assess different scenarios yielding to a sharing a global emissions budget over the horizon 2020–2050; finally, in Section 5, we discuss the insight provided by this modeling approach on the possible future of the Paris Agreement and we conclude. In the Appendix, we recall the mathematical formulation of the different meta-models that have been used.

2 Representing Macroeconomic Impacts of Climate Policies with GEMINI-E3

We use the CGE GEMINI-E3[1] model to compute abatement costs and welfare losses associated with climate policies. An overview of the model has been given in several recent publications, in particular [1].

2.1 GEMINI-E3 Calibration

GEMINI-E3 is calibrated for a base year 2007 using the GTAP-8 energy-economy database [22], which includes 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. The elasticities of substitution appearing in CES functions are guess estimated based on existing literature. The validation of the model has been made through comparison with other CGE models in collaborative EU projects and at EMF (the Energy Modeling Forum) [23, 24].

In this assessment exercise, we define 8 regional aggregates. They include China (CHI), India (IND), European Union (EUR), United States of America (USA), and major fossil fuel exporters (OPEC (OPE) and Russia (RUS)). The remaining countries are separated into two groups, according to their per

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[1] The GEMINI-E3 model is continuously improved to better represent future possibilities of energy substitution. The model focuses on assessing the incremental capital cost of restructuring the economy, i.e., new investments in the production sectors and in housing aimed at improving energy efficiency. From a comprehensive survey, one has identified in each sector the technologies that can significantly increase energy efficiency. One assumes that these new technologies induce more capitalistic equipment and more energy-efficient production. These new technologies are introduced into the model through technical progress (positive for energy and negative for capital). In order to be accepted by the industrial sectors, the change must be profitable, which means that the discounted savings in operating costs over the lifespan of the investment must be greater or equal to their price increase. This methodology has been implemented in housing, industry, and transportation sectors. In the model, one offers the possibility to use carbon capture and sequestration (CCS) technology only for coal-fired power plant. When the total cost of the CCS technology is lower than the carbon price, one assumes that all investments in power plants using coal are done with CCS. Simulation is based on a CCS cost of US$100 by ton of CO_2.

capita gross national income (GNI), i.e., other developed countries (ODC) for the 15 countries which have an average GNI of more than $12,736 in 2014 (according to World Bank data and classification) and other developing countries (DEV) for the countries under this limit. The sectors considered in the model, aggregated from the GTAP classification, are listed in Table 1.

2.2 Computing Welfare Losses, Marginal Abatement Costs, and Carbon Prices with GEMINI-E3

2.2.1 The Compensative Variation of Income

The pitfalls of estimating correctly the marginal abatement costs and the carbon prices in countries subject to different forms of taxation of energy have been described in [25]. A consistent measure of welfare cost is households surplus, which can be based either on the compensative variation of income (CVI) or on the equivalent variation of income (EVI). Though theoretically slightly different, they yield very close results as the change in the structure of prices is of a limited magnitude, and energy has a small share in average production cost of the economy or households budget. Deriving demand by households from a utility function then allows one to have a direct economic measure of the welfare cost of abatement policies. Households surplus may be directly reckoned from the numerical results of scenarios, for every year and every country/region, and they can be aggregated in various ways: either weighted by exchange rates and summed for a given year or period or discounted through interest rates for a given country and then measuring the total discounted cost of the abatement policy. For a given period, households' surplus is representative of the total welfare gain if the other elements of final demand (except exports) are held constant. This is the case of the final demand of government, which is exogenous in the model as in most general equilibrium models. Concerning productive investment, which is endogenous in the model and is sensitive to changes in relative prices (and in particular to the change in the relative price of consumption and capital goods), surpluses calculated annually are representative of welfare cost if its total investment is constrained to be constant in the scenario, a constraint that has been imposed in the model.

Table 1 Sectors and industrial classification

Sector	Description
01	Coal
02	Crude oil
03	Natural gas
04	Petroleum products
05	Electricity
06	Agriculture
07	Energy-intensive industries
08	Other goods and services
09	Land transport
10	Sea transport
11	Air transport

2.2.2 Computing Marginal Abatement Cost

The marginal abatement cost is computed from the marginal welfare loss at constant prices of foreign trade. In a context of emissions trading, in which the permits trade is operated by government, the welfare loss must be deflated by the social value of goods, since the permits are exchanged against tradable goods. Social values of goods differ from market prices of a quantity that is equal to the marginal cost of public funds (MCPF).

To eliminate the effects of changes in the relative prices of foreign trade, one has to subtract the marginal gain (or loss) from changes in the terms of trade (GTT) to marginal welfare loss. This yields the so-called deadweight loss (DWL) of taxation. In other terms, the marginal abatement cost is equal to the marginal deadweight loss (DWL) of taxation deflated by MCPF. The estimation, performed along an abatement trajectory compatible with the 2°C goal, is done in three steps:

- First, one estimates the welfare cost of an additional abatement for each country and each period. This provides a direct measure of the welfare loss, which is the sum of the marginal GTT and the marginal DWL, which represents the searched quantity;
- The second step is to estimate the marginal cost of public funds (MCPF). The approach is the same: difference between the welfare loss of a unit increase in global taxation and the associated change in the terms of trade;
- The last step, in order to make MACs comparable and the basis for permits trading, is to deflate then from the exchange rate.

Table 2 gives the (average on the total period) values of the marginal cost of public funds by region. They show significant differences that could be due to two possible causes: the first is the efficiency of the fiscal system, but this is not easily quantifiable; the second is the weight of taxes on the economy, its share on the total GDP. Part of the taxes corresponds to redistribution between economic agents and households in particular and should not weigh on the effective (or net) fiscal pressure. Public outlays, and in particular public consumption, appears to have more leverage on the MCPF.

2.3 Representing an International Carbon Market

In the presence of an externality such as GHG emissions, an approach favored by economists consists in taxing the

Table 2 Marginal cost of public funds by country/region (average 2010–2050)

USA	EUR	ODC	RUS	CHI	IND	OPE	DEV
1.066	1.216	1.130	1.202	1.031	1.019	1.161	1.101

emissions or equivalently subsidizing the abatements. Markets of emission rights provide also a mean to internalize the climate change cost. Both the tax and the market approaches prove to be equivalent in an efficient economy context as they both define the same price of carbon. From the start of the endeavor by international organizations, like the United Nations at the forefront with the UNFCCC or the European Union, pricing the GHG emissions was contemplated. In the Kyoto Protocol, even though a universal carbon tax or a world market of emissions rights was not formally retained, the so-called flexibility mechanisms had been introduced as an ersatz of a world carbon pricing scheme. It must be remembered that in the Kyoto Protocol, only developed countries were assigned commitments and emission ceilings for the year 2020. In a perfect world, the simplest solution is to set a uniform carbon tax that would be implemented by all countries. But this supposes that there are no distortions, fiscal or economic, in various countries and in world trade. The mere fact that in the initial situation the concerned countries are taxing fossil energy at different rates and some even subsidizing its consumption by firms and/or households, contradicts the assumption. The difference may be significative, already between developed countries and particularly between industrialized and developing countries or fossil energy exporters like OPEC members.[2] Independently of the above-mentioned distortions, a uniform carbon tax has two other drawbacks. The first is that its implementation can be bypassed by countries through fiscal policy or other devices that would reduce or even cancel the effect of the carbon tax, like, e.g., subsidizing equipments that produce or use fossil energy.[3] In other terms, there is no incentive for countries to really implement the carbon price and there is no obvious mean for other countries and international organizations to check the reality of the carbon pricing. Then, such a device may not operate in a decentralized way, due to the difficulty to find a supra-national authority to perform the necessary checking and verification. The second drawback is that a uniform carbon tax has equity effects, within the countries although these effects can be corrected by domestic fiscal policies, but more importantly among different countries, these effects being possibly corrected by transfer payments that will be difficult to design.

A world market of tradable permits does not exhibit these drawbacks. The only initial collective decisions are (i) setting a long-term trajectory of world GHG emissions or more simply a global cumulative CO_2 emissions budget over the period considered and (ii) distributing the emission rights to countries. Once the rights are allocated to countries, the market can work in a totally decentralized way. It is up to each country to determine its domestic abatement policy (and the corresponding domestic tools which can be a domestic carbon tax or a domestic carbon market) and its position on the international carbon market, i.e., its supply or demand of permits according to the equilibrium price. Operators in the world market may only be the countries because they detain the rights which represent their commitments if they do not trade. They are accountable towards the world community of these commitments and the use of their rights. It is however possible for countries to delegate the trade of permits to domestic firms under a condition. It must be understood that in such a system, the world and the domestic equilibrium carbon prices have no reason to coincide. In brief, one could say that the difference represents the existing distortions in the given country, which is mainly the level of existing energy taxes. A country with no (distorting) energy taxation would obtain a domestic tax somehow equal to the world price, while a country with distorting initial taxation would exhibit a lower domestic taxation (and a country subsidizing fossil energy a higher domestic price in order to cancel the effect of subsidies). Then a country could give delegation to domestic firms in order to operate in the world market under the condition of compensating the difference (if the world price is higher the firm is positively compensated of the difference).[4]

2.4 Fair Burden Sharing

The remaining issue is how to envision a fair allocation of the permits or, more simply as we will see shortly, a fair sharing of a safety cumulative CO_2 emissions budget. Global climate justice is a thorny issue (see the recent survey [30]) and several different fairness criteria can be invoked. It might be considered that, at least in the initial years, for a sake of implementability and simplicity the allocation of permits will not be far from the

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[2] In a paper published in 1999 [26], the energy taxation in the USA and European countries was compared and a gap equivalent to US$100 by ton of carbon (around US$25 by ton of CO_2) was found. The authors concluded that the USA should start implementing a carbon tax of this level before the European countries start taxing GHG emissions.

[3] This behavior is known in the economic literature as "greasing."

[4] This mechanism of a world carbon market under distortions, i.e. in a second-best setting à la Boiteux [27], has been theorized in a 1999 paper [28] presented at the Paris 1999-IEW conference with numerical simulations displayed in another paper presented at the same conference and also in [25]. An important issue is the efficiency of the market, according to the Pareto criterion. In second-best problems, in particular in the present one where the issue is to determine the equilibrium (in the markets of goods and in the market of permits) between countries implementing each a second-best policy, Pareto efficiency is not in general strictly obtained when there are not simplifying assumptions such as in the Diamond and Mirrlees paradigm [29] (where the firms profits are totally taxed). In the present case, Pareto efficiency can be shown to turn up under separability conditions which are not exactly verified in the real world. Nevertheless it is permitted to consider that the equilibrium is not far from Pareto-efficiency, and the eventual gap to efficiency can be assessed through numerical simulations of macroeconomic models.

so-called grand-fathering rule. This would contain the volume of trade and financial transfers to moderate value, acceptable to all countries and easier to manage. In the long run, an allocation proportional to the population is a rule often considered as being equitable since it gives the same rights to every human.[5] For example we could explore a rule based on a combination of 80% grand-fathering and 20% proportionality to population, in 2020 and which evolves to 20% grand-fathering and 80% proportionality to population in 2050. However, we will see that this permit allocation rule tends to induce big discrepancies in the relative welfare losses for different groups of countries. The recent US decision to withdraw and the consideration of stranded fossil fuel asset risks, tend to show that a fairness criterion based on the equalization of the relative welfare losses (in % of business as usual (BaU) household consumption), would be easier to get accepted in an international agreement. Finally, it has been shown that allowances trading is efficient over time only if banking and borrowing are permitted [31]. With such provisions, market prices will reflect opportunity costs which will lead to an efficient choice of abatement measures [32]. This is the approach that will be followed when one defines a meta-model to represent the actions of countries on a world carbon market. One imposes a coupled constraint in the form of a global CO_2 cumulative emissions budget, which is now determined to be around 800 Gt CO_2 for the period 2015–2050. Then the negotiation will be around the sharing of this budget among the countries. These countries will then use their emission rights by defining strategically both their emissions abatements and their supply of emission rights on the market. The fair sharing of this global emissions budget should yield balanced relative welfare losses among the different coalitions of countries.

3 Scenarios for the Future of Paris Agreement

In this section, one recalls that the INDCs are largely insufficient to provide the abatements necessary to reach the 2°C goal. The discrepancies in the implied welfare losses with respect to a BaU situation for the different groups of countries are also reported. A benchmark abatement scenario is proposed for the planning horizon 2015–2050 and one discusses the possible organization of an international carbon markets in 2030.

3.1 BaU and Benchmark Scenarios

As a reference, let us consider first the simulation provided by GEMIN-E3 of a BaU scenario on the period 2015–2050. Assumptions on population are based on the forecast done by the United Nations, with the median fertility variant. In 2050, the world population will reach 9.27 billion inhabitants. Global GDP growth decreases slightly over the period from 3% annually to 2.7%. The crude oil price is assumed to reach US$150 per barrel in 2050. Household consumptions, which will be used later on to normalize the welfare losses, are shown in Table 3 and CO_2 emissions for the BaU scenario are shown in Table 4.

Let us consider now a benchmark global abatement scenario that is compatible with a 2°C long-term goal (see [33]). The proposed abatement trajectory is shown in Fig. 1 and Table 5. Compared with the BaU scenario, it implies a decrease of emissions between 2010 and 2050 of over 50%. It gives a cumulative budget of CO_2 equal to 803 Gt CO_2 over the period 2015–2050. This CO_2 budget is consistent with the ones computed by Baer et al. [34] which are equal for 2°C and 1.5°C respectively to 913 and 518 Gt CO_2 for the same period. But the authors recognize that “the IPCC budgets suggests that such pathways actually carry substantially higher risks than previously believed.” Our midpoint budget between 913 and 518 is a conservative option with a greater chance of keeping warming below 2°C.

3.2 INDCs Will Not Suffice

In [1], the INDCs were expressed in terms of contributed abatements. Indeed the INDCs are not always declared as abatements but are rather contributions of various sorts like emissions levels, carbon intensity, and abatements. INDCs expressed in terms of energy-related CO_2 emissions pledges in 2030 are shown in Table 6. We note that, at the world level, the emission pledges, unconditional[6] and conditional, are well below what is assumed in the BaU scenario. Globally, it appears that INDCs emissions pledges in 2030 would be one third to half way to the benchmark 2°C trajectory (see Fig. 1). At regional level, it appears that for developed countries INDCs lead to emissions much below the BaU ones; this is particularly the case of USA and EUR, not exactly for ODC for which there is a gap of around 15%. Russia and OPEC are emitting less than the BaU, and it is the same for Developing Countries. The assessment is totally different for China and India, whose INDCs yield emissions that are close or above BaU scenario and significantly above Benchmark scenario. The combined excess of these two countries explains most of the world gap with respect to the 2°C trajectory.

These assessments referred to physical quantities, i.e., abatements pledged in INDCs, are compared to BaU trend and to the benchmark emissions trajectory. Another evaluation can also be obtained using implicit carbon prices underlying

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[5] This is for the mitigation issue and does not preclude others transfers under the adaptation issue, with tools such as the Green Climate Fund.

[6] The unconditional target refers to an initial objective of GHG emissions for a reference year or period. The target, called conditional, provides additional GHG abatement efforts conditional on some circumstances or events (e.g., actions of other parties, contingent on broader mitigation efforts of other countries, the provision of financial transfers by other countries, and technology or capacity building support).

Table 3 Household consumption in the BaU scenario (billion 2007 US$)

	2015	2020	2030	2040	2050
USA	11,353	12,404	16,142	20,715	26,209
EUR	11,093	11,833	14,543	17,584	21,087
OEC	6377	6801	8266	10,019	11,900
RUS	800	865	1148	1510	1966
CHI	2442	3143	5565	7522	11,574
IND	1122	1408	2212	3245	4298
OPE	1152	1381	2107	2860	4066
DEV	5542	6408	8733	11,798	16,166
World	39,881	44,243	58,717	75,254	97,266

Table 4 CO_2 emission in the BaU scenario (Mt CO_2)

	2015	2020	2030	2040	2050
USA	4998	4935	5612	5643	5881
EUR	3201	3459	3664	3875	4139
ODC	3430	3282	3453	3633	3876
RUS	1469	1668	1902	2214	2613
CHI	9085	9835	12,210	13,423	15,325
IND	2066	2487	3186	3779	4261
OPE	2298	2317	2951	3647	4580
DEV	5218	5547	5877	7093	8596
World	31,765	33,530	38,855	43,307	49,271

the INDCs, i.e., the taxes that should be implemented in the different countries to reach their respective contribution's target. These implicit prices are computed in the CGE model. Of course, if the target defined in the INDC proves to be above the BAU emissions, the carbon price is equal to zero as no effort is required. The carbon prices obtained with GEMINI-E3 are presented in the Table 7. They are compared with carbon prices also obtained by other groups, like e.g. the European Commission [35], using a variety of models, like RITE, WITCH, DNE21+, MERGE [36], and EPPA [37].

The high carbon price values obtained for industrial countries and the low (even null) for China and India show the difference in ambition of the respective INDCs. OPEC and other developing countries exhibit moderate carbon price, which show a lesser ambition than developed countries but a significantly higher one than China and India.

Finally, GEMINI-E3 provides an estimate of the implied welfare cost for the 189 countries which have submitted INDCs on the UNFCCC platform.[7] Table 8 reports these estimates when the conditional INDCs are implemented without and with emissions trading. Without trading, the global cost of the INDC scenario is limited to 0.8% of household consumption in 2030. Energy exporting countries suffer the main burden coming from loss of energy exporting revenues. In contrary, China and India experience a welfare improvement due to limited commitments and gains from terms of trade. Industrialized countries with significant CO_2 abatements have a welfare cost driven mainly by abatement costs (i.e., DWL).

Implementing an emissions trading system (ETS) would reduce the worldwide cost of the Paris Agreement. The global cost shifts from 0.8 to 0.3% of household consumption. All regions benefit from the participation in an ETS. The permit price is equal to US$22.[8] The main winners are industrialized countries with a welfare cost close to zero and India, which can sell significant amount of permits. In contrary, the Chinese welfare cost is nearly unchanged with emission trading.

The fact that INDCs in their present level are far from being consistent with the long term target of limiting temperature warming to 2°C (and a fortiori for well under 2°C) set in the Paris Agreement is generally acknowledged. (The precise gap varying from one assessment to the other.) More ambitious commitments have to be taken, by developed countries, although supress but as we will see the margin is fairly thin for them, and mainly by emerging countries such as China and India as they appear to have still substantial flexibility in mastering the growth of their emissions.

3.3 A World Carbon Market in 2030 Compatible with the Benchmark Scenario

Considering the large heterogeneity in the INDCs and their ambition, and in particular the very limited commitment by major emitters like China and India, designing a carbon price mechanism appears as a true challenge. Moreover, there is a debate between defenders of a uniform carbon price that would be agreed upon by all or a limited group of voluntary countries and those who advocates for a cap and trade system. With GEMINI-E3, one can easily simulate the effect of a common carbon tax imposed worldwide. By adjusting the tax, one can drive the global emission level to be consistent with the benchmark trajectory. The resulting estimates of the marginal abatement cost along the emissions trajectory for each group of countries, computed as indicated in Section 2.2.2, are given in Table 9.

These figures show significant differences among countries. This reflects the effect of other existing taxes which weigh, together with the carbon tax, on the effective carbon price. As discussed in Section 2.2, it would be preferable to envision a global world market of tradable permits.

We can simulate, for the year 2030, a global world market of tradable permits with total world emissions compatible with

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[7] See http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx

[8] Without US participation to the Paris Agreement, the permit price is equal to US$16.

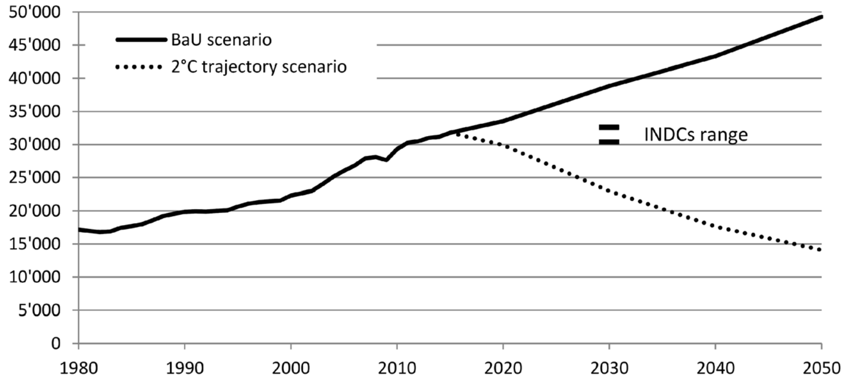

Fig. 1 CO_2 energy-related emissions in the BaU and 2 °C trajectory scenarios in Mt CO_2

a 2°C benchmark emissions trajectory. To define the permits allocations, we use a weighted criterion consisting of 70% grand-fathering and 30% proportionality to population. Grand-fathering implies a minimum deviation from the existing situation. Its merit is to limit the potential volume of trade between the actors on the carbon market. It has no other virtue, and in particular on equity concerns. On the opposite, proportionality to population is often viewed as the archetype of equity, treating all humans as equals and endowed of the same rights on the environment. A proportionality rule applied in the short run may be disruptive in generating too important volumes of trade and thus very high financial transfers.

Table 10 presents the results of simulation for this scenario. Carbon price reaches US$80 in 2030.

The big sellers of permits are China, India, OPEC, and developing countries. Buyers are all industrial countries.

Table 11 indicates the worldwide cost, estimated at 1.1% of household consumption (HC) in 2030 and the distribution of this welfare loss among the different groups of countries. The quotas allocation rule limits the cost for industrialized countries (always lower than 0.9% HC) and creates some incentives to developing and emerging countries. China and mostly India benefit from revenues coming from selling of permits; however, the gains of emissions selling are not sufficient to compensate the abatement costs for other developing countries (DEV). The main losers are energy exporting countries (RUS and OPE) with significant losses higher than 13% of HC. Such imbalances would probably be politically unacceptable by the countries suffering higher welfare costs.

In the rest of this paper, we will look at the possibility to define a climate agreement that would balance the welfare losses among the different groups of countries, using a game theoretical approach.

4 Fair Sharing of the Safety Cumulative CO_2 Emission Budget

As exemplified by the announced US withdrawal from the Paris treaty, the definition of a commonly agreed abatement path for the whole world is not yet obtained. One must expect the countries to play a noncooperatiave game, when implementing the abatements that are necessary to reach the 2°C target. In this section, we explore the burden sharing issue by letting different groups of countries use strategically their emission rights in exploiting the flexibility in the world carbon market.

4.1 A Safety Cumulative CO_2 Emissions Budget

There is now a consensus among climate scientists about a safety CO_2 cumulative emission budget compatible with a 2°C target. In 2013, a scientific assessment of IPCC[9] was that "cumulative emissions of carbon dioxide (CO_2) largely determine global mean surface warming by the late 21st century and beyond."[10] The benchmark emissions trajectory proposed above corresponds to a cumulative budget of 0.803 trillion tonnes of CO_2 and it would remain around one trillion tonnes as a residual budget to be spent after 2050, before reaching a situation of net 0 emissions.

As already indicated, negotiations on more stringent abatement paths should take place in order to achieve the goal of Paris Agreement. These forthcoming negotiations will be complex involving macroeconomic evaluation, monitoring, technological assessment and transfers, development aid for emerging economies, etc. [7]. But at the end of the day, the outcome should be a fair sharing of the safety cumulative CO_2 emissions budget. As already discussed, the easiest way to implement an economic mechanism permitting the attainment

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[9] IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Cli-mate Change, Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[10] It appears that for a given level of cumulative CO2 emissions, the planet experiences about the same level of warming irrespective of whether that CO2 is emitted fast or slow [6]. The safety cumulative emissions budget for the entire anthropocene, i.e. since the beginning of industrial era, compatible with a 2 °C target at the end of twenty-first century is estimated at one trillion tonnes of carbon (3.7 trillion tonnes of CO2), half of which had already been emitted by 2015.

Table 5 CO_2 emission profile in the benchmark scenario

Period	Mt CO_2
2015	31,765
2020	29,919
2030	22,968
2040	17,625
2050	14,086

of these objectives is to assume the implementation of a world market for emission permits, where each group of countries taking part in the agreement receives an endowment in permits to be used dynamically on a market with full banking and borrowing. With such an economic mechanism, the marginal abatement costs will be harmonized as equal to the world price and the trading of permits will realize the necessary transfer payments to obtain the international cooperation on burden sharing. This leads us to address the burden sharing and fair agreement issues by building a dynamic game meta-model where countries strategies correspond to their carbon permit supply and emissions abatements and where the payoffs are computed from the marginal abatement cost functions obtained from statistical emulation of GEMINI-E3. The mathematical description of the meta-model is provided in the Appendix 1.

4.2 A Game Design Problem

It has already been showed in [1, 2, 4] that the search for a fair burden sharing can be formulated as a "game design" problem. In summary, a "safety cumulative CO_2 emissions budget", denoted Bud, imposes a constraint on cumulative emissions from all countries over the planning horizon (2015–2050). The negotiations should determine how this global budget is distributed among the groups of countries. These countries will then use their respective budget to supply an international emissions trading market. The situation will be very much like an oligopolistic exploitation of non-renewable resource. A Nash equilibrium describes the "optimal" use of their permits by the different groups of countries. Let $\theta_j \in [0, 1]$ be the share of global emissions budget given to group of countries j, with $\sum_{j=1}^{m} \theta_j = 1$. The θ parameters are thus design variables that will change the game structure, and therefore the equilibrium solution. The negotiations are thus represented by the choice (design) of these shares (θ's) that will lead to a Nash equilibrium solution which satisfies some fairness or equity criteria. The mathematical formulation of the game design problem is detailed in Appendix 1.

Table 6 Unconditional and conditional CO_2 energy-related emissions in 2030 for INDCs and BaU scenario (Mt CO_2)

	Unconditional	Conditional	BaU
USA	3604	3490	5612
EUR	2414	2414	3664
ODC	2711	2653	3453
RUS	1622	1514	1902
CHI	11,172	9776	12,210
IND	3439	3336	3186
OPE	2420	2300	2951
DEV	5237	4922	5877
World	32,621	30,404	38,855

4.3 Equilibrium Solutions with an Emissions Profile Compatible with the Benchmark Scenario

For a cumulative emission budget (Bud) of 803 Gt CO_2, which is consistent with the benchmark scenario, and different values of θ's, we solve the noncooperative game of permit supply over the planning period 2015–2050. The yearly discount factor (β) is set to 95%, which corresponds roughly to a 5% discount rate.

4.3.1 Imposing the Abatement Profile of the Benchmark Scenario

As shown in the following numerical simulations, the full banking and borrowing flexibility will yield a global abatement schedule very different from the benchmark scenario even assuming a similar cumulative emissions budget. To obtain a global abatement schedule close to the one computed in the benchmark scenario, it suffices to add, for the periods 2020, 2030, and 2040, new coupled constraints imposing the global supply of permits on the world market to be greater than or equal to the corresponding emissions level in the benchmark scenario. The mathematical formulation is reported and explained in Appendix 2. This would mean that, in the negotiation of the climate treaty an additional coupled constraint is imposed on the players (groups of countries).

First, we extend the analysis of previous section, which was uniquely dealing with the period 2030, to the whole horizon 2015–2050. Hence, we consider a sharing of the budget that is based on the rule retained in Section 3.3 consisting of 70% grand-fathering and 30% proportionality to population. Imposing that the global emissions schedule follows the benchmark emissions profile given in Fig. 1 and Table 5, we computed the equilibrium under coupled constraints[11] on global supply of permits at periods 2020, 2030, and 2040, as given in Tables 12 and 13. Table 12 gives the carbon price at each period and we find the price of \$80/t of CO_2 in 2030 already obtained in Section 3.3. Table 13 shows the budget allocated, using this rule, and the resulting welfare cost. The

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[11] As shown in [38], one should expect a manifold of equilibria indexed over a weighting of the players. Here, we show the results for the equilibrium corresponding to an equal weight given to all players.

Table 7 Various estimates of the carbon price underlying INDCs in 2030 (source: [35–37])

	GEMINI-E3	WITCH	DNE21+	GCAM	MERGE	GEM-E3	EPPA
USA	77	101	109	100	40	53	99
EUR	93	116	177	100	45	53	130
ODC	57						
RUS	12		4	2	0	0	
CHI	7	33	1	12	23	29	< 5
IND	0	0	0	19	0	0	0
OPE	48						
DEV	40						

Table 8 Welfare cost (in % of household consumption) of scenarios INDCs without and with emissions trading, year 2030

	No trade			With trade			
	DWL (%)	GTT (%)	Total (%)	DWL (%)	GTT (%)	Trade (%)	Total (%)
USA	0.7	− 0.1	0.6	0.4	− 0.1	0.2	0.4
EUR	1.2	− 0.2	1.0	0.3	− 0.2	0.1	0.2
ODC	0.7	− 0.2	0.6	0.4	− 0.2	0.1	0.3
CHI	0.3	− 0.9	− 0.6	0.9	− 0.9	− 0.6	− 0.6
IND	0.0	− 0.9	− 0.8	− 0.2	− 0.9	− 1.0	− 2.0
RUS	0.9	1.9	2.8	0.9	1.9	0.1	2.8
OPE	0.5	3.5	4.0	0.6	3.5	− 0.1	4.0
DEV	0.9	0.3	1.2	0.9	0.3	0.0	1.1
World	0.8	0.0	0.8	0.5	0.0	0.0	0.3

global cumulative discounted welfare cost is equal to 1.7% of the cumulative discounted households consumption. The main losers are OPEC and Russia, followed by China. India has a significant welfare gain coming from permits selling and gains from terms of trade. The USA and other industrialized countries have limited welfare losses as well as other developing countries (DEV).

We may simulate different combinations of grand-fathering and per capita rules for the quota allocations. As expected, the global cost equal to 1.7% of discounted household consumption will remain the same for all quota allocations. The emissions abatement profile and carbon prices are also unchanged; only the burden sharing between regions is modified. Figure 2 shows the welfare cost per regions with a share of per capita rule ranging from 100 to 0% (i.e., a share of grand-fathering rule ranging from 0 to 100%). Of course, an allocation based only on population benefits to developing countries (India and DEV), and penalizes industrialized regions. Interesting is the case of China where welfare loss decreases with the weight given to grand-fathering. It confirms that regarding climate change mitigation, China can be viewed as an industrialized economy. Russia and OPEC suffer always high welfare cost linked to energy export revenues losses. However, Russia welfare loss decreases with higher share of grand-fathering, whereas OPEC welfare is unchanged with respect to the weighting. It is clear that none of these quota allocations will tend to equalize the welfare losses per regions.

Table 9 Marginal abatement cost by country/region and by period resulting from a common carbon tax (in constant 2007 US$)

	2020	2030	2040	2050
USA	6	89	359	411
EUR	14	154	454	567
ODC	10	112	391	476
RUS	10	76	378	379
CHI	7	75	441	653
IND	8	83	464	511
OPE	0	50	182	270
DEV	7	80	259	340

A “Rawlsian” solution of the game design problem will be such that the welfare losses in percentage of household consumption are equalized. This solution is shown in Table 14. Compared to the previous scenario combining 70% grand-fathering and 30% per capita, this scenario transfers allocations from industrialized countries and India to energy exporting countries. In contrary, the quotas allocated to

Table 10 World market of tradable permits in 2030

	Emis.*	Abat.*	Quotas*	Purchases of permits*	Financial transfers**
USA	3720	1892	2719	1001	− 80.7
EUR	3144	520	2158	986	− 79.5
ODC	2635	819	1917	717	− 57.8
CHI	5732	6479	6073	− 341	27.5
IND	1390	1795	2470	− 1079	87
RUS	996	905	943	53	− 4.3
OPE	1352	1599	1608	− 256	20.7
DEV	3999	1878	5080	− 1081	87.2
World	22,968	15,887	22,968	0	0

*in million ton CO_2, **in billion of US$

Table 11 Welfare cost (in % of household consumption)

	DWL (%)	GTT (%)	Trade (%)	Total (%)
USA	0.7	− 0.5	0.5	0.7
EUR	0.5	− 0.7	0.5	0.4
ODC	0.8	− 0.6	0.7	0.9
CHI	3.4	− 3.4	− 0.5	− 0.5
IND	− 0.4	− 3.2	− 3.9	− 7.5
RUS	5.7	7.1	0.4	13.2
OPE	1.4	13.1	− 1.0	13.6
DEV	1.9	0.9	− 1.0	1.9
World	1.2	− 0.1	0.0	1.1

China and DEV are nearly unchanged. Compensating decreases in energy exporting revenues for OPEC and Russia requires huge additional amounts of quotas (21.7% and 8.9% respectively) even though these two regions represent less than 10% of the world population.

4.3.2 Equilibrium with Full Flexibility on Global Permit Supply at Each Period

The previous scenarios assumed that the global emissions trajectory is given and that regions have to collectively follow this profile per decade. We now relax this constraint, and assume that only the cumulative CO_2 emissions on the period 2015 to 2050 are constrained to be upper-bounded by the safety emissions budget Table 15 and 16.

With a 5% discount factor the world discounted welfare loss is equal to 1.3%, the gain is significant with respect to the benchmark scenario (i.e., the cost decreases by 24%). As shown in Fig. 3, with a 5% discount rate, more abatements are implemented in the two first decades and less after.

Table 12 Carbon price (2007 US$)/t CO_2—benchmark scenario

Period	2020	2030	2040	2050
Price	10	80	263	533

Increasing the discount factor would delay CO_2 abatement in the future (see Fig. 3) and of course decreases the discounted welfare losses by definition.

4.4 Full Optimization vs. Equilibrium

Indeed, every time a Nash equilibrium solution is displayed, the question arises of how much is this solution distant from a full optimization one. We show in this section that a full optimization approach would not lead to a significant change in the global welfare loss. In a full optimization approach, each group of countries will be told how much to abate in each period. The allocation of permits, in each period could then be decided in such a way as to balance the welfare losses in each period, as well as globally for the whole planning horizon. The mathematical formulation is given in Appendix 3.

Table 13 Benchmark scenario 2015–2050—70% grand-fathering and 30% per capita rule

	Budget		Welfare cost†			
	In Mt CO_2	In %	DWL (%)	GTT (%)	Trade (%)	Total (%)
USA	87,931	10.9	0.8	− 0.6	0.3	0.6
EUR	67,586	8.4	0.4	− 0.8	0.4	0.0
OEC	60,730	7.6	0.7	− 0.3	0.8	1.2
RUS	32,186	4.0	4.5	8.3	3.0	15.8
CHI	211,308	26.3	6.8	− 4.3	0.1	2.6
IND	89,006	11.1	3.6	− 3.9	− 5.7	− 6.0
OPE	63,506	7.9	4.6	16.7	2.4	23.7
DEV	190,833	23.8	1.9	1.0	− 1.5	1.4
World	803,087					1.7

† Discounted welfare cost in % of discounted consumption

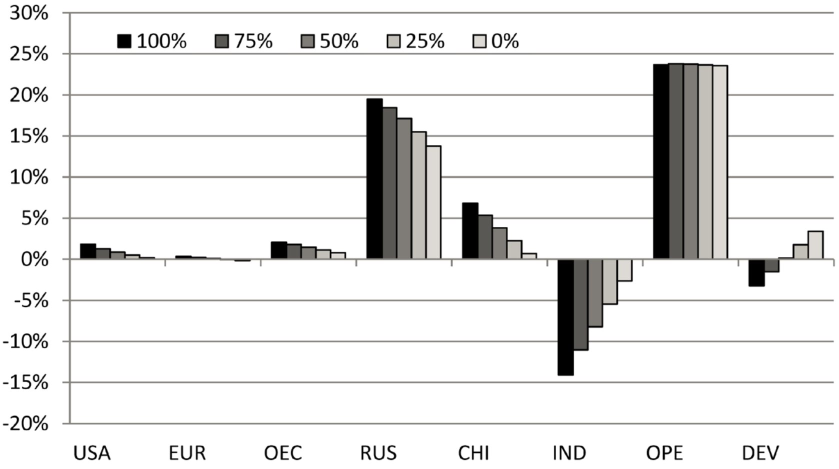


Fig. 2 Discounted welfare cost in % of discounted consumption—benchmark scenario with per capita rule ranging from 100 to 0%

Table 14 Benchmark scenario 2015–2050—Rawlsian rule

	Budget		Welfare cost[†]			
	In Mt CO_2	In %	DWL (%)	GTT (%)	Trade (%)	Total (%)
USA	38,581	4.8	0.8	− 0.6	1.4	1.7
EUR	10,315	1.3	0.4	− 0.8	2.1	1.7
OEC	39,940	5.0	0.7	− 0.3	1.3	1.7
RUS	79,670	9.9	4.5	8.3	− 11.1	1.7
CHI	218,689	27.2	6.8	− 4.3	− 0.8	1.7
IND	31,814	4.0	3.6	− 3.9	1.9	1.7
OPE	209,015	26.0	4.6	16.7	− 19.6	1.7
DEV	175,062	21.8	1.9	1.0	− 1.3	1.7
World	803,087					1.7

[†] Discounted welfare cost in % of discounted consumption

4.4.1 Simulation Results

The results of numerical simulations of the optimization model, using a yearly discount factor $\beta = 95\%$ are shown in Tables 17 and 18. An immediate observation is that these results are very close to the Nash equilibrium under coupled budget constraint. Indeed, welfare costs are very marginally lower (2 billion 2007 US$) and the total budget allocations and the carbon prices as well as emissions profiles are similar in the two approaches.

There is however a big difference between the permit supply schedule of the different groups of countries in the game equilibrium and in the optimization approaches. Even though in both cases the relative welfare losses are equalized (Rawlsian rule), the supply of permits is very different in both cases, as shown in Table 19. Permit supplies are indeed much lower in 2020, in particular for the USA, China, India, and developing countries, and globally higher in periods 2040 and 2050. These significant changes in allocation patterns are the consequence of the welfare loss equalization at each period. This indicates that the countries behaving in a noncooperative way would not seek to equalize the welfare losses at each period.

Table 15 Carbon price (2007 US $)/t$CO_2$—equilibrium solution scenario

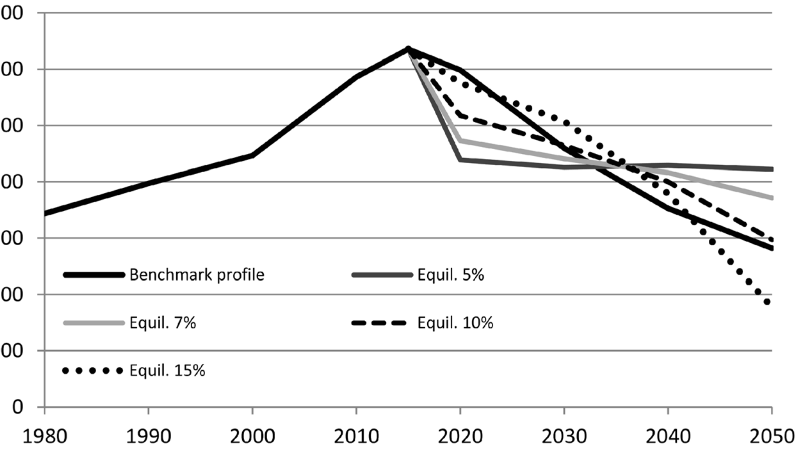
	2020	2030	2040	2050
Carbon price	63	102	165	268

Table 16 Equilibrium solution scenario 2015–2050—Rawlsian rule

	Budget		Welfare cost[†]			
	In Mt CO2	In %	DWL (%)	GTT (%)	Trade (%)	Total (%)
USA	58,378	7.3	0.7	− 0.8	1.4	1.3
EUR	19,689	2.5	0.3	− 1.0	2.0	1.3
OEC	58,326	7.3	0.5	− 0.3	1.1	1.3
RUS	71,796	8.9	3.3	10.5	− 12.5	1.3
CHI	212,877	26.5	5.9	− 5.0	0.5	1.3
IND	34,544	4.3	3.0	− 4.8	3.1	1.3
OPE	174,368	21.7	3.1	20.1	− 21.9	1.3
DEV	173,108	21.6	1.3	1.2	− 1.2	1.3
World	803,087					1.3

[†] Discounted welfare cost in % of discounted consumption

Fig. 3 Emissions trajectory



5 Insights and Conclusion

In this paper, we have used numerical simulations performed with a CGE model, associated with a meta-modeling approach to provide an economic assessment of the INDCs and a benchmark abatement scenario compatible with the Paris Agreement. We also have provided an analysis of what could be a fair burden sharing to achieve the goal of 2°C that is a key objective of the agreement. In this endeavor, we have shown that the favored approach to implement a global climate policy will be to organize a world carbon market on which the countries will be the actors determining their domestic policy in order to achieve equality of the marginal abatement cost (MAC) with the world carbon price. To simulate such a market, the challenge was to compute MAC correctly. We have shown how this could be done with GEMINI-E3, defining the deadweight loss of taxation and the gains from the terms of trade for each group of countries under consideration. With this tool at our disposal we have been able to evaluate the welfare losses incurred by different groups of countries if they implement their respective INDCs and we have simulated the world carbon market in 2030, for a benchmark abatement scenario compatible with the 2°C objective. Assuming an allocation rule mixing grandfathering and proportionality to population, we have evaluated the resulting welfare loss for different groups of countries. To take into account the inclination of several (groups of) countries, like, e.g., the USA or fossil energy-exporting countries, to play noncooperatively and their insistence to obtain a fair sharing of the burden, we have used a meta-model in the form of noncooperative game subject to a coupled constraint corresponding to the cumulative CO_2 emissions budget that is compatible with the 2°C objective. The insights gained from this exercise are (i) as already widely recognized, the INDCs are not in line with the 2°C objective; (ii) a simulation of the welfare losses of different groups of countries, along a benchmark scenario, with an allocation of emission rights mixing grandfathering and proportionality to population gives unequal degrees of burden for different groups of countries, as expressed in relative welfare loss; (iii) a noncooperative game approach, subject to a cumulative CO_2 emissions budget, allows the identification of a sharing of this budget among countries that yields an equally distributed burden; and (iv) the abatement schedule and carbon price obtained in this noncooperative solution are very close to the one obtained in fully cooperative solution, which shows that the noncooperative behavior does not yield to a loss of efficiency, provided that all countries abide to satisfying the cumulative emissions budget limit, or in other words if all countries accept the 2°C objective.

Table 17 Welfare cost (discounted cost in % of discounted household consumption) and budget allocated per regions—optimization solution scenario

	Cost (%)	Budget allocated	
		In Mt CO_2	In %
USA	1.3	58,452	7.3
EUR	1.3	19,484	2.4
OEC	1.3	58,128	7.2
RUS	1.3	71,665	8.9
CHI	1.3	213,278	26.6
IND	1.3	34,691	4.3
OPE	1.3	174,174	21.7
DEV	1.3	173,216	21.6
World	1.3	803,087	

Table 18 Carbon price (2007 US$)/t CO_2—optimization solution scenario

	2020	2030	2040	2050
Carbon price	65	101	163	266

Table 19 Differences in Mt CO_2 permit supplies in the optimization approach compared to the game equilibrium one

	2020	2030	2040	2050
USA	− 348	114	31	223
EUR	− 14	3	9	0
OEC	111	9	− 110	− 4
RUS	266	− 42	− 94	− 139
CHI	− 505	153	280	− 26
IND	− 203	6	65	175
OPE	530	− 135	− 140	− 259
DEV	− 53	− 90	59	147
World	− 216	19	101	77

Funding Information This research is supported by the Qatar National Research Fund under Grant Agreement No. NPRP10-0212-170447.

Appendix: Mathematical Description of the Meta-models

Appendix 1: The Game Design Problem.

Design variables θ_j, share of the safety emission budget given to group of country *j*. 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 coalition *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 at each period 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. Using statistical emulation an abatement cost is estimated as a function of the abatement realized w.r.t. the BaU scenario.

$e_j(t)$	emission level for group of countries *j* in period *t*;
$q_j(t)$	abatement level for player *j* in period *t*;
$p(t)$	carbon price in period *t*;
$AC^t_j(q_j(t))$	abatement cost for player *j* in period *t*;
$MAC^t_j(q_j(t))$	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 group of countries *j*.

Parameters

Bud	safety budget: global safety emission budget;
$bce_j(t)$	BaU emissions for group of countries j in period t;
$\alpha_{0j}(t)$, $\alpha_{2j}(t)$, $\alpha_{2j}(t)$, $\alpha_{3j}(t)$, α_{4j} j(t))	coefficients in the abatement cost function;
$\mu_{0j}(t)$, $\mu_{1j}(t)$	coefficients in the gain from the terms of trade function;
β	periodic discount factor;
hc_j	discounted household consumption in BaU scenario over the planning horizon.

Payoffs for the game of quotas supply The players (groups of countries) try to minimize (resp. maximize) the discounted sum of net surplus losses (resp. gains). The payoff is therefore defined as 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.

$$W_j = -\sum_t \beta^t \left\{ AC^t_j\left(q_j(t)\right) - p(t)\left[w_j(t) - e_j(t)\right] - \mathrm{GGT}_j(t)\right\}, \tag{1}$$

where $q_j(t) = bce_j(t) - e_j(t)$

Functions estimated by statistical emulation of GEMINI-E3: They are the abatement cost

$$AC^t_j\left(q_j(t)\right) = \alpha_{0j}(t) + \alpha_{1j}(t)q_j(t) + \alpha_{2j}(t)q_j(t)^2 + \alpha_{3j}(t)q_j(t)^3 + \alpha_{4j}(t)q_j(t)^4 \tag{2}$$

and the gains in the terms of trade

$$\mathrm{GTT}_j(t) = \mu_{0j}(t) + \mu_{1j}(t)\sum_i q_i(t). \tag{3}$$

The statistical emulation of GEMINI-E3 is based on a sample of 200 scenarios that simulate different possible world climate change policies.

Objective of the game design problem One applies a Rawlsian criterion of fairness [39].

$$z = \max_{\theta}\min_{j}\frac{W_j^*}{\mathrm{hc}_j}, \tag{4}$$

where W_j^* is the Nash equilibrium payoff for the game designed by the choice of the θ's. 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.

We describe now how to characterize the Nash equilibrium in the game of quotas supply. There are m players (groups of countries) indexed $j = 1, \ldots, m$, that generate emissions $e_j(t)$ on periods $t \in \{0, 1, \ldots, T-1\}$. Let $\Omega(t) = \sum_{j=1}^{m}\omega_j(t)$ denote the total supply of permits on the market at period t and $p(t, \Omega(t))$ the clearing permit price at period t.

We assume a competitive market for emissions permits, which clears at each period. Given a price $p(t)$, each player chooses emissions so as to (5)

$$\max_{e_j(t)}\{\pi_j^t(e_j(t)) + p(t)(w_j(t)-e_j(t))\}.$$

where $\pi_j^t(e_j(t)) = -AC_j^t(\mathrm{bce}_j(t)-e_j(t))$ is the economic benefit associated with emission level $e_j(t)$ at period t. The equilibrium conditions of profit maximization and market clearing are then

$$p(t) = MAC_j^t(\mathrm{bce}_j(t)\text{-}e_j(t)) = \frac{\partial}{\partial e_j}\pi_j^t(e_j(t)) \qquad t = 0, \ldots, T-1; \quad j = 1, \ldots, m, \tag{5}$$

$$\Omega(t) = \sum_{j=1}^{m} e_j(t), \qquad t = 0, \ldots, T-1. \tag{6}$$

These conditions define after-trade equilibrium emissions, $e_j(t, \Omega(t))$, and the permit price $\mathrm{p}(t, \Omega(t, t)$. Differentiating (5) and (6), we can compute the derivatives

$$\frac{\partial}{\partial\Omega}\mathrm{p}(t,\Omega(t)) = \frac{1}{\sum_{j=1}^{m}\frac{1}{\pi_j^{t''}\left(\mathrm{e}_j^t(\Omega^t)\right)}} \tag{7}$$

$$\frac{\partial}{\partial\Omega}\mathrm{e}_j(t,\Omega(t)) = \frac{1}{\sum_{i=1}^{m}\frac{\pi_j^{t''}\left(\mathrm{e}_j^t(\Omega^t)\right)}{\pi_i^{t''}\left(\mathrm{e}_j^t(\Omega^t)\right)}}. \tag{8}$$

Applying standard Kuhn-Tucker multiplier method, with multipliers ν_j, and exploiting the equality (5), we obtain the following first order necessary conditions for a Nash equilibrium

$$\begin{aligned} v_j = {} & \beta_j^t MAC_j^t(\mathrm{bce}_j(t)-\mathrm{e}_j(t,\Omega(t))) \\ & + \frac{\partial}{\partial\Omega}\mathrm{p}(t,\Omega(t))\omega_j(t)-\mathrm{e}_j(t,\Omega(t))) \\ & t = 0, \ldots, T-1; \quad j = 1, \ldots m. \end{aligned} \tag{9}$$

$$0 = v_j\left(\theta_j\mathrm{Bud}-\sum_{t=0}^{T-1}\omega_j(t)\right) \tag{10}$$

$$0 \le \theta_j\mathrm{Bud}-\sum_{t=0}^{T-1}\omega_j(t) \tag{11}$$

$$0 \le v_j. \tag{12}$$

Appendix 2: Imposing the Benchmark Abatement Scenario

To obtain in the game the same global abatement schedule as in the benchmark scenario, it suffices to add, for the periods 2020, 2030, and 2040, new coupled constraints imposing the global supply of permits on the world market to be greater than or equal to the corresponding emissions level in the benchmark scenario. More formally, we introduce the new parameters

$$\mathrm{BMGE}(t):$$

$$\text{global } \mathrm{CO}_2 \text{ emissions at period } t \text{ in benchmark scenario,} \quad t = 1, \ldots, T-1;$$

and the new constraints

$$\sum_{j=1}^{m}\omega_j(t) \ge \mathrm{BMGE}(t), \qquad t = 1, \ldots, T-1. \tag{13}$$

The NOCs will be modified in an obvious way.

Appendix 3: Full Optimization vs. Equilibrium

To find the fully optimal solution, one solves the following problem:

$$\tilde{V}^{\star} = \min_{\mathrm{q}(\cdot)}\sum_t\sum_j\beta^t\left\{AC_j^t\left(q_j(t)\right)\right\}, \tag{14}$$

$$\text{s.t.} \quad \mathrm{Bud} \ \ge \ \sum_t\sum_j\left\{\mathrm{bce}_j(t)-q_j(t)\right\}, \tag{15}$$

where, as defined above, $\mathrm{bce}_j\,(t)$ denotes the BaU emissions and $q_j\,(t)$ the abatement level for group of countries j in period t; Let $q^*(\cdot)$ denotes the optimal abatement path for all countries. The optimal emissions levels are determined by

$$e_j^*(t) = \mathrm{bce}_j(t) - q_j^*(t).$$

We form the Lagrangian

$$\mathscr{L} = \sum_t \sum_j \beta^t AC_j^t(qj(t)) - \pi \left(\mathrm{Bud} - \sum_t \sum_j \left[\mathrm{bce}_j(t) - qj(t) \right] \right), \tag{16}$$

where π is the multiplier (dual variable) associated with the global emissions budget constraint.

The optimality conditions are

$$\pi^* = \beta^t MAC_j^* \left(q_j^t(t) \right), \quad \forall j, t, \tag{17}$$

$$\pi^* \geq 0, \tag{18}$$

$$\mathrm{Bud} \geq \sum_t \sum_j \{ \mathrm{bce}_j(t) - q_j(t) \}, \tag{19}$$

$$0 = \pi^* \left(\mathrm{Bud} - \sum_t \sum_j \left[\mathrm{bce}_j(t) - q_j^*(t) \right] \right) \tag{20}$$

These are also the market clearing conditions for an international emissions trading scheme. The carbon price at t will thus be $p^\star(t) = \pi^\star \beta^{-t}$.

Fair Allocation of Emission Permits

We consider that fairness is obtained when the net costs relative to the respective consumption levels in the BaU scenarios are equalized. The balance in net cost per unit of consumption is obtained at period t if the following relation holds true

$$K^*(t) = \frac{W_j^*(t)}{\mathrm{hc}_j(t)} = \frac{W^*(t)}{\mathrm{Hc}(t)}, \tag{21}$$

where

$$W_j^*(t) = AC_j^t \left(q_j^*(t) \right) - p^*(t) \left[\omega_j(t) - e_j^*(t) \right] - \mathrm{GTT}_j^*, \tag{22}$$

and $W^\star(t)$ with Hc (t) are world level values. The fair allocation of permits at period t would then be

$$\omega_j(t) = \frac{1}{p^*(t)} \left\{ AC_j^t \left(q_j^*(t) \right) + p^*(t) e_j^*(t) - \mathrm{GTT}_j^* - K^*(t) \mathrm{hc}_j(t) \right\}$$

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