Assessment of Climate Agreements over the Long Term with Strategic Carbon Dioxyde Removal Activity

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Abstract

In this paper we extend a game theoretic meta-model used to assess the future of Paris agreement to the time horizon 2100 and we include in the strategic decisions of the negotiating coalitions the use of Carbon Dioxyde Removal (CDR) technologies. The meta-game model is calibrated through statistical emulation of GEMINI-E3, a world computable general equilibrium model. It permits the identification of a fair sharing of the safety cumulative emissions budget, compatible with a 2°C warming. In this scenario CDR technologies play an important strategic role in the second half of the century and leave some room for fossil fuels in the primary energy balance.

Keywords: Climate negotiations, meta-Game, carbon dioxide removal, negative emissions

1 Introduction

The aim of this paper is to explore the long term relevance of negative emissions generated by Carbon Dioxide Removal (CDR) for the attainment of Paris agreement goals. More precisely, the considered CDR technologies

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are Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC). For this purpose, we extend to the horizon 2100 a burden sharing meta-game model that we used to explore climate policies in [4, 5, 6] and we introduce BECCS and DAC activities as part of the strategies that different groups of countries can adopt in the long term. In the simulations performed with this extended model, we observe the possible impact of the introduction of these technologies on the definition of a fair sharing of a cumulative emissions budget.

In many scenario simulations performed with integrated assessment models, where the goal is to maintain a temperature change below 2°C at the end of the century, negative emissions play an important role, starting in 2050 and permitting reaching a zero-net emission regime around 2070, see e.g. [2, 31, 24, 17, 49]. Of particular interest are the scenarios proposed in the Shell reports [44, 45] and the analysis of these scenarios done by the MIT Global change program [34]. The technology of choice to produce negative emissions is biomass fueled power plants with carbon capture and sequestration BECCS [2, 3, 38, 43]. However the approach is not without risks and limitations as noted in this quote from [16]:

> *One drawback to this approach will be scale, because an estimated 180,000 square miles of arable land (roughly 6% of the land area of the contiguous United States) will be required to capture one billion metric tons of CO_2 per year ([19, 13]). Another concern is the life-cycle carbon balance. Greenhouse gas emissions may be associated with growing, harvesting, and transporting the biomass, as well as land-use changes associated with growing energy crops.*

In other scenarios built with integrated assessment models, the negative emissions are obtained from CDR, including DAC technologies; a model WITCH with DAC has been used in [11] and more recently a MERGE model with DAC has been proposed [28] as well as an analysis performed with the REMIND model [47].

DAC involves the chemical sorption of dilute CO_2 from flowing air and the release of concentrated CO_2 while regenerating these chemicals[1]. As already indicated above, there are alternative CO_2 removal (CDR) approaches like e.g. storage of additional carbon on the land (achieved by afforestation, reforestation, and the insertion of ecologically inert biomass, e.g. charcoal, into soil), or capture of CO_2 from bioenergy facilities (capture of part of

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[1] See the APS report [46].

the carbon in biomass can occur during the conversion of the biomass to power and fuels) accompanied by sequestration (the CO_2 that is captured was removed earlier from the atmosphere by photosynthesis). Indeed, DAC and biocapture strategies can co-exist.

DAC is ineffective if the CO_2 emissions associated with the energy to run the capture plant become comparable to the quantities of CO_2 that the plant removes from the input gas mixture. One way around the net-carbon problem for DAC is to generate power and heat from fossil fuels at the DAC site and to capture the CO_2 from these facilities. Subsequent steps would involve a unified system to transport and store the CO_2 captured from both the local energy production plants and the DAC facility. Other approaches would use non-carbon (renewable or nuclear) energy sources. In principle, any concentrated stream of CO_2 produced by DAC or industrial CO_2 capture could be recycled into low-carbon fuels, such as low-carbon diesel. CO_2 recycled into fuels is sometimes proposed as an alternative to CO_2 disposal[2]. This shows that there are several options for the introduction of DAC technologies in the energy system to attain a zero-net emission regime worldwide. It appears that the potential for implementing DAC will vary considerably among world regions. The first criterion to assess the potential of DAC is the possibility to have access to a cheap zero-emission energy and heat source (e.g. natural gas with CCS, solar or nuclear); a second element is the potential for sequestration (e.g. depleted oil and gas reservoirs, aquifers, etc.).

DAC technologies might be quite expensive. Current assessments envision a cost between \$200 and \$600 per ton of CO_2 removed [16, 11, 28, 21]. However the price of carbon in 2050 given by different integrated assessment and macroeconomic models is of this order of magnitude. If an international emissions trading scheme is implemented, the countries benefitting of an advantage in developing DAC activities, will have the possibility to "mine" emission rights. These rights will be a resource traded on a market, with very little logistical cost. It could very well be that the very same countries that benefitted from an oil and gas rent that could disappear in an assertive climate policy [7] will, in the future, obtain a negative emissions rent through the possible implementation of large-scale DAC technologies. To explore such scenarios we propose to adapt and extend to the period 2020–2100 a Meta-game model already used to assess fair burden sharing in the agreement that should follow the Paris agreement, up to year 2050

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[2] https://news.nationalgeographic.com/2018/06/carbon-engineering-liquid-fuel-carbon-capture-neutral-science/

without access to CDR. The original model defines a Nash equilibrium in a game of supply of emission rights on a world carbon market. The agreement is described as a sharing of the safety cumulative emissions budget compatible with the temperature change objective (e.g. 1 billion tons of carbon since the beginning of the industrial era for the 2°C objective [1]). The linking of peaking temperature change with cumulative emissions is addressed in many references, in particular [1, 12, 29, 30, 50]. Recently, in [39] it is claimed that

> *.. the most appropriate carbon budget estimate, for a greater than 66% chance of limiting warming below 2°C, is 590-1240* $GtCO_2$ *from 2015 onwards...*

Therefore, as a consequence of the Paris-agreement, all the parties, jointly should limit their cumulative emissions to this safety budget. The idea that a climate policy should be oriented toward a fair sharing of cumulative emissions has been proposed in [15, 36] and developed in [4, 5, 6], using a Meta-game model that we intend to extend to capture the possible impact of BECCS and DAC technologies. We consider 10 groups of countries, or coalitions, like e.g., European Union, USA, Gulf Cooperation Council, Latin America, etc. In each group there are several countries sharing similar economic structure. As indicated above, the burden sharing issue is reduced to the sharing of the safety cumulative emissions budget. To assess the economic consequences of a proposed sharing rule, one must assume that an "optimal" use of the global emissions budget will be made, or, at least that a "second best" solution should be reached, corresponding to a Nash equilibrium among the parties. For that purpose we assume that an international market for emissions permits will be implemented and that the participating countries will have full banking and borrowing options to manage their respective emissions budget shares. A strategic variable is then the supply of permits that each group of countries forming a party will put on the market at each time period. The total supply of permits will determine a world price of carbon and emissions abatement levels that equate the price to the respective marginal abatement costs in the different parties. This will also determine the welfare losses, with respect to a Business as Usual (BAU) situation, the gains in the terms of trade, and the buying and selling of permits. Another strategic variable is the level of activity in carbon dioxide removal (CDR). Through the use of CDR technologies the countries can generate negative emissions, which replete their respective emissions budgets. At each period, the net cost for a coalition is the sum of the welfare losses plus the CDR cost minus the gains from the terms of trade and the gains (minus the cost) from the selling (buying) of permits. The “second best” solution is obtained by assuming that the parties play a Nash equilibrium with payoffs defined by minus the discounted sum of their net costs over the rest of the 21$^{\text{st}}$ century plus the discounted cost over an infinite horizon of the limit steady state solution with zero-net emissions. This equilibrium result will permit a comparison of the relative welfare losses, expressed as the discounted sum of GDP losses relative to the BAU situation. A fair (Rawlsian) burden sharing should be the one which minimizes the maximum of the relative welfare losses.

The rest of the paper is organized as follows: In Section 2, we review the literature of CDR in integrated assessment models; In Section 3, we summarize the Meta-game model that will be used; In Section 4, we describe the extension of the macro-economic model that has permitted a consideration of the horizon 2100, and, we present the calibration of the costs and potentials of DAC/BECCS for different world regions; In Section 5, we present the simulations of different scenarios of budget sharing and we propose a possible fair sharing agreement; Section 6 concludes by interpreting the simulation results and proposing further research development.

2 A literature review of CDR in integrated assessment models

2.1 Shell Sky scenario

The Sky scenario [45] proposes a way to abide to the emissions profile that is proposed in the Paris agreement. In this scenario, net-zero emissions is reached in 2070, followed by net-negative emissions until the end of the 21$^{\text{st}}$ century. To reach this zero-net and then negative-net situation, a profound transformation toward an electricity based energy system is proposed. In this scenario fossil energy still represents a 15% share of the global energy system at the end of 21$^{\text{st}}$ century. In 2070, solar counts for 32% of primary energy source, wind for 13%. Oil, natural gas and coal count for 22% and are associated with CCS. Bioenergy counts for 14% and is also associated with CCS. BECCS becomes a negative emission technology, which pumps CO_2 out of the atmosphere while producing electricity. The reliance on BECCS as the main technology generating negative emissions may impose an important environmental stress as the logistics of production and transport of biomass feedstock will enter in competition with food production and reforestation.

2.2 WITCH

Recently other scenarios have been proposed, using WITCH [10, 49], where DAC is introduced as a promising technology for the attainment of a net-zero emissions regime. The model takes into account the regional distribution of DAC, with Transition Economies, and Middle East and North Africa being the two biggest DAC players. These energy exporting countries have a comparative advantage in carrying out DAC because of the large CO_2 storage availability and abundant energy resources that can be used for power and high-temperature heat at the DAC facilities, the cost of which accounts for around 30% of the total cost of DAC in 2100 (see Fig. A1 in appendix for a breakdown of DAC costs). Compared with the base case, in 2100 an additional 65 EJ of power and 298 EJ of high-temperature heat will be needed to fuel the DAC plants, resulting in an increase of 84% in primary energy supply. For DAC plants only, apart from the increased demand of gas, which provides all the heating, the additional electrical demand is mainly met by nuclear (36% in 2100) and renewables (wind and solar, 57% in 2100).

2.3 MERGE

In [28], the model MERGE-ETL [25, 26] is used to show that DAC technology can play an important role in realizing deep decarbonization goals and in the reduction of regional and global mitigation costs with stringent targets. In the 2°C and 1.5°C scenarios analyzed DAC technology captures 21 and 40 $GtCO_2$ in 2100, respectively. Zero-net emissions is attained in 2075 and 2040 respectively, and very large negative emissions occur at the end of the planning horizon. It is also noted that "*One important limit in the development of DAC is storage capacity. For this reason, countries with large storage capacity benefit the most from the availability of such technology...*"

2.4 TIAM

In [43] a version of TIAM is used to assess the potential BECCS and other capture and storage processes in achieving stringent climate objectives. The potential for storage was evaluated at 14.8 Gt of CO_2 per year of which 12.6 Gt of CO_2 can be stored in deep saline aquifers

2.5 REMIND

In [33, 22], the authors consider bioenergy and direct air capture of CO_2 from ambient air [20], both in combination with CCS, and re- and afforestation.

DAC captures CO_2 from ambient air, which requires large amounts of heat and electricity. An estimated 430–570\$/t-CO_2 makes it a rather expensive option compared to both BECCS at 36\$/t-CO_2 and afforestation at 24 (18–30) \$/t-CO_2, but on the upside DAC is less dependent on the location and requires only little land.

3 A model of strategic exploitation of the net cumulative emission budget

3.1 Model assumptions

We assume that there is a safety global emission budget over the time horizon 2016-2100, which is set to 1170 Gt of CO_2 to be consistent with the recent IPCC report [40] on pathway to 2°C. Climate negotiations bear on the sharing of this global safety emission budget among an ensemble of groups or coalitions of countries. Each coalition regroups countries with similar macroeconomic structure; therefore a coalition will be characterized by a BAU emissions path and an abatement cost function at each period. We describe 10 countries/regions that are listed in Table 1. We also assume that there exists an international emissions trading system. The coalitions will thus supply permits on the market, using strategically their share of the cumulative safety emissions budget. Through the development of CDR activities like BECCS and DAC, a coalition can replenish or increase its own cumulative emission budget. We assume that BECCS and DAC will be the technologies of choice for CDR, with different costs and potentials among the coalitions. In the rest of this section we formulate a dynamic game to represent this competition and characterize an open-loop Nash equilibrium solution.

Table 1: Countries/regions described in our model

EUR	European Union (28 countries)
USA	United States of America
CHI	China
IND	India
GCC	Gulf Cooperation Council
RUS	Russia
ASI	Rest of asian countries
OEE	Other energy exporting countries
LAT	Latin America
ROW	Rest of the World

3.2 Model's equations

Variables and parameters

$j \in \{1, \ldots, m\}$**:** index of coalition;

$t \in \{1, \ldots, T\}$**:** time periods;

$\delta(t)$**:** duration of time period t;

B**:** global safety emission budget over the time horizon $[0, T]$;

θ_j**:** share of the global emission budget allocated to coalition j;

$b_j = \theta_j B$**:** cumulative emission budget for coalition j at period 0;

$b_j(t)$ remaining emission budget for coalition j at end of period t;

$\nu_j(t)$**:** K-T multiplier for global budget constraint of coalition j at period t;

$\omega_j(t)$**:** supply of emission permits at period t by coalition j;

$\Omega(t)$**:** total supply of emission permits at period t;

$v_j(t)$**:** negative emission activity (CDR) by coalition j at period t;

$v_j(0)$**:** negative emission activity (CDR) by coalition j at period 0;

$\kappa_j(v_j(t), t)$**:** cost of CDR for coalition j at period t;

$q_j(t)$**:** abatement level by coalition j at period t;

$\epsilon_j(t)$**:** BAU emission level by coalition j at period t;

$e_j(t)$**:** emission level by coalition j at period t;

$e_j(0)$**:** emission level by coalition j at period 0;

$\varpi_j(q_j(t), t)$**:** Abatement cost for coalition j at time t;

$\mathbf{e}(t)$**:** vector of all m emission levels at period t;

$\pi_j(\mathbf{e}(t), t)$**:** Net abatement cost (including changes in the terms of trade) for coalition j at time t;

$\gamma_j(\sum_{k=1}^{m} q_k(t), t)$**:** gains from the changes in terms of trade for coalition j at time t;

β_j**:** discount factor for coalition j equals 3%;

Emissions from abatement. This equation relates the abatement and emission levels relative to BAU

$$e_j(t) = \epsilon_j(t) - q_j(t) \tag{1}$$

Emission budget constraints. Let $b_j(\tau)$ denote the remaining emission budget, for region j at the end of period τ, $\tau = 0, \ldots, T-1$. We approximate the integral of net emissions up to period τ, using trapezoidal method. The part of the emissions budget remaining at period τ is thus defined as

$$0 \leq b_j - (\frac{1}{2}\sum_{t=0}^{\tau-1} \delta(t+1)(\omega_j(t) + \omega_j(t+1) - v_j(t) - v_j(t+1))), \qquad j = 1, \ldots, m, \quad \tau = 0, \ldots, T-1. \tag{2}$$

By imposing non negative remaining budgets, we eliminate the possibility for each "player" to perform short-selling of future DAC activities.

This expression can also be rewritten

$$b_j - (\frac{1}{2}\delta(1)(\omega_j(0) - v_j(0)) + \frac{1}{2}\sum_{t=1}^{\tau-1}(\delta(t) + \delta(t+1))(\omega_j(t) - v_j(t)) + \frac{1}{2}\delta(\tau)(\omega_j(\tau) - v_j(\tau))) \geq 0, \quad j = 1, \ldots, m, \quad \tau = 0, \ldots, T-1. \tag{3}$$

Net-zero emissions in final period. At the end of the planning horizon one must reach a zero-net emission regime. So there should be a coupled constraint of the form.

$$\sum_j (v_j(T) - e_j(T)) \geq 0. \tag{4}$$

However, this constraint will probably be redundant with the emission budget constraints and we will not consider it.

Emissions trading. An international carbon market determines a price and emissions levels.

$$\begin{aligned} p(t) &= \frac{\partial}{\partial q_j(\cdot)}\varpi_j(q_j(t), t) = -\frac{\partial}{\partial e_j(\cdot)}\varpi_j(\epsilon_j(t) - e_j(t), t) & (5) \\ \Omega(t) &= \sum_{k=1}^{m} e_k(t); \quad j = 1, \ldots m. & (6) \end{aligned}$$

The price and emission levels are thus functions of the total permit supply $\Omega(t)$, thus denoted $\tilde{\mathbf{e}}(\Omega(t), t)$ and $\tilde{p}(\Omega(t), t)$, respectively.

As shown in Helm [14], the derivatives w.r.t. Ω of price and emission levels are given by

$$\begin{aligned} \tilde{p}'(\Omega, t) &= \frac{1}{\sum_{j=1}^{m} \frac{1}{\frac{\partial^2 \varpi_j(q_j, t)}{\partial q_j^2}}} && (7) \\ \tilde{e}_j'(\Omega, t) &= \frac{1}{\sum_{k=1}^{m} \frac{\frac{\partial^2 \varpi_j(q_j, t)}{\partial q_j,^2}}{\frac{\partial^2 \varpi_j(q_k, t)}{\partial q_k^2}}} && (8) \end{aligned}$$

respectively. Since $\Omega(t) = \sum_{j=1}^{m} \omega_j(t)$ the derivatives w.r.t. $\omega_j(t)$ are the same as the derivatives w.r.t. $\Omega(t)$.

Payoffs. The periodic net cost to coalition j includes the abatement cost plus the cost of buying permits on the market (negative if selling) and is given by

$$\psi_j(t) = [\pi_j(\tilde{\mathbf{e}}(\Omega(t), t) + \kappa_j(v_j(t), t) - \tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))], \quad (9)$$

where

$$\pi_j(\mathbf{e}(t), t) = \varpi_j(q_j(t), t) - \gamma_j(\sum_k p_k(t), t). \quad (10)$$

The payoff coalition j is defined by the integral of the discounted periodic costs

$$J_j(\cdot) = \frac{1}{2}\delta(1)\psi_j(0) + \frac{1}{2}\sum_{t=1}^{T-1}(\delta(t) + \delta(t+1))\psi_j(t) + \frac{1}{2}\delta(T)\psi_j(T),$$
$$j = 1, \ldots, m. \quad (11)$$

We assume that the supply of permits and DAC activities of each coalitions are strategically defined as the open-loop Nash equilibrium for the game defined by payoffs (11) and constraints (1)-(8).

3.3 Nash equilibrium conditions

We write now the first order conditions for a Nash equilibrium solution. The existence of a solution is implied by the convexity of the cost functions.

Denoting $\nu_j(t)$ the K-T multiplier of the emission budget constraint (3) for coalition j, we may write the Lagrangian for each player j as given by

$$\mathcal{L}_j(\cdot) = \frac{1}{2}(\delta(1)\psi_j(0) + \delta(T)(\psi_j(T)) + \frac{1}{2}\sum_{t=0}^{T-1}(\delta(t) + \delta(t+1))(\psi_j(t)+$$
$$\nu_j(t)(b_j - \frac{1}{2}\sum_{s=0}^{t-1}\delta(s+1)(\omega_j(s) + \omega_j(s+1) - v_j(s) - v_j(s+1)))$$
$$j = 1, \ldots, m. \quad (12)$$

Complementarity conditions for $\omega_j(t)$

$$\begin{aligned} 0 &\leq \beta_j^t \frac{\partial}{\partial \omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t), t) - \tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))] + \nu_j && (13) \\ 0 &\leq \omega_j(t) && (14) \\ 0 &= \omega_j(t)\left\{\beta_j^t \frac{\partial}{\partial \omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t), t) - \tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))]\right. \\ &\quad \left. +\nu_j\right\}. \quad t = 1 \ldots T && (15) \end{aligned}$$

Developing the expression

$$\begin{aligned} &\frac{\partial}{\partial \omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t), t) - \tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))] = \\ &\qquad \frac{\partial}{\partial \sum_k q_k(t)}\gamma_j(\sum_k q_k(t), t)\frac{\partial}{\partial \omega_j(t)}(\sum_{k=1}^m e_k(\Omega(t), t)) \\ &\qquad - (\frac{\partial}{\partial q_j(t)}\varpi(q_j(t), t) - \tilde{p}(\Omega(t), t))\frac{\partial}{\partial \omega_j(t)}e_j(\Omega(t), t)) \\ &\qquad - \tilde{p}(\Omega(t), t) - \frac{\partial}{\partial \omega_j(t)}\tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t)), \quad (16) \end{aligned}$$

and using the relations $\frac{\partial}{\partial q_j(t)}\varpi(q_j(t), t) = \tilde{p}(\Omega(t), t)$ and $\sum_{k=1}^m e_k(\Omega(t), t) = \Omega(t)$ that hold on the emission permit market the complementarity condition (15) can be rewritten more simply

$$\begin{aligned} \omega_j(t)&\left\{-\beta_j^t[-\frac{\partial}{\partial \sum_k q_k(t)}\gamma_j(\sum_k q_k(t), t) + \tilde{p}(\Omega(t), t)\right. \\ &\qquad \left. + \frac{\partial}{\partial \omega_j(t)}\tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))] + \nu_j\right\} = 0. \quad (17) \end{aligned}$$

Complementarity conditions for $v_j(t)$

$$
\begin{aligned}
0 &\leq \beta_j^t \frac{\partial}{\partial v_j(t)} \kappa_j(v_j(t), t) - \nu_j && (18) \\
0 &\leq v_j(t) && (19) \\
0 &= v_j(t) \left\{ \beta_j^t \frac{\partial}{\partial v_j(t)} \kappa_j(v_j(t), t) - \nu_j \right\}. && (20)
\end{aligned}
$$

Complementarity conditions for $\nu_j(t)$

$$
\begin{aligned}
0 &\leq b_j - \frac{1}{2} \sum_{s=0}^{t-1} \delta(s+1)(\omega_j(s) + \omega_j(s+1) - v_j(s) - v_j(s+1)) && (21) \\
0 &\leq \nu_j(t) && (22) \\
0 &= \nu_j(t) \left\{ b_j - \frac{1}{2} \sum_{s=0}^{t-1} \delta(s+1)(\omega_j(s) + \omega_j(s+1) - v_j(s) - v_j(s+1)) \right\} \\
&\quad , j = 1, \ldots, m. && (23)
\end{aligned}
$$

4 Model calibration

4.1 CO_2 emissions and payoff functions

We use the GEMINI-E3 model [8, 9] to calibrate the dynamic game model. GEMINI-E3 is a worldwide multi-country, multi-sector, computable general equilibrium (CGE) model that has been specifically designed to assess energy and climate change policies. GEMINI-E3 is used to compute the CO_2 emissions and economic variables within the business as usual (BAU) scenario and calibrate the payoff functions (π_j). The methodology used to calibrate our game theory model using an applied CGE is detailed in our previous papers, e.g. see Appendix 2 in [6]. In short, various climate policies are simulated by GEMINI-E3, then we perform econometric estimations of the abatement cost ($\varpi_j(q_j(t), t)$) and gains from term of trade ($\gamma_j(\sum_{k=1}^{m} q_k(t), t)$) functions. However, the time horizon of GEMINI-E3 is limited to the first part of our century (i.e. up to 2050), therefore we have to implemented a procedure extending the variables for the years 2070 and 2100. We use a versatile representation based on a steady state growth approach for the end of our century.

$$
\begin{aligned}
\frac{gdp_j(t)-gdp_j(t-1)}{gdp_j(t-1)} &= \frac{pop_j(t)-pop_j(t-1)}{pop_j(t-1)}\cdot(1+\nu_j^1(t))^{\delta(t)}\\
\frac{e_j(t)-e_j(t-1)}{e_j(t-1)} &= \frac{gdp_j(t)-gdp_j(t-1)}{gdp_j(t-1)}\cdot(1+\nu_j^2(t))^{\delta(t)}\\
\nu_j^1(t)=\nu_j^1(t-1)-\delta(t)&\cdot(\nu_j^1(t-1)-\nu_j^1(T))/(\delta(T-1)+\delta(T))\\
\nu_j^2(t)=\nu_j^2(t-1)-\delta(t)&\cdot(\nu_j^2(t-1)-\nu_j^2(T))/(\delta(T-1)+\delta(T))\\
\nu_j^1(T)&=\nu^1 \quad \forall j\\
\nu_j^2(T)&=\nu^2 \quad \forall j
\end{aligned}
\tag{24}
$$

First, we select a demographic scenario among the projections done by United Nations [48] and determine the working population[3] ($pop_j(t)$). Then, we follow a production function approach linking GDP per capita ($gdp_j(t)/pop_j(t)$) to a total productivity factor (TFP) $\nu_j^1(t)$. We assume that for each region the TFP converges to a common value (ν^1) at the end of our century. Finally, we assume that for each region CO_2 emissions per GDP ($e_j(t)/gdp_j(t)$) decrease with an annual rate that converges to a single value ν^2. Thus we can simulate various BAU scenarios by setting a value for the three parameters defined above, demographic scenario, ν^1 and ν^2.

The abatement functions ($\varpi_j(q_j(t),t)$) are extrapolated for the years 2070 and 2100 by assuming a proportionally rule with respect to the level of abatement for the year 2050. The GTT functions ($\gamma_j(\sum_{k=1}^m q_k(t),t)$) in 2070 and 2100 are supposed unchanged with respect to 2050 figures.

4.2 Techno-economic assumptions for DAC and BECCS

4.2.1 Levelized costs

We use the most recent description and assessment of an operational DAC process [21]. The process requires either 8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWh of electricity, per ton of CO_2 captured. For each ton of CO_2 captured, the process delivers 1.48 tons of dry CO_2 which must be sequestered. The extra 0.48 tons comes from the burning of natural gas to provide electricity and heat. If power is obtained from zero emission technology, like nuclear or solar plants, the ratio of CO_2 sequestered per CO_2 captured in the air falls to 1.29. We thus consider in this paper two levelized costs for DAC technologies, i.e., 300\$/t-CO_2 and 350\$/t-CO_2, to

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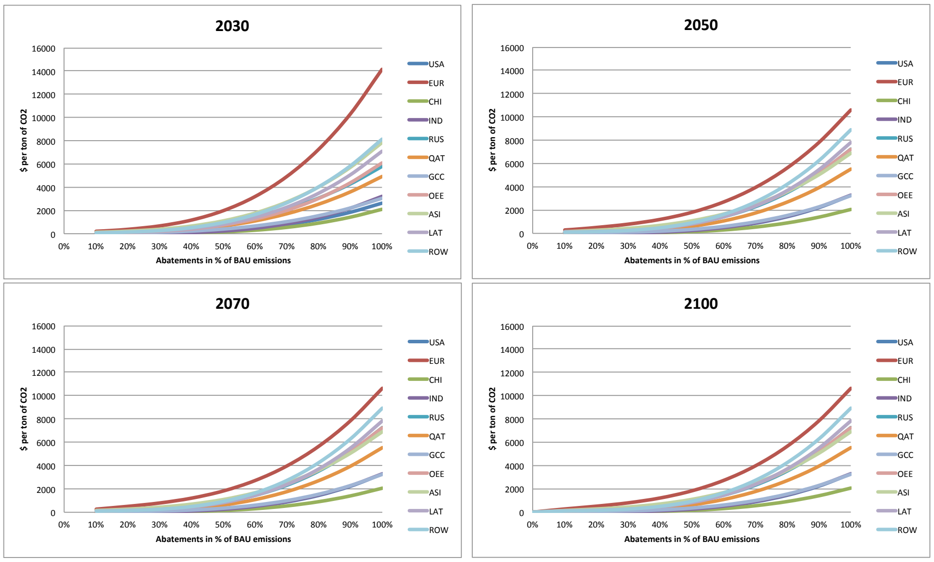
[3] Male and female population aged from 20 to 64.


2030

2050

2070

2100

Figure 1: Marginal Abatement Cost functions

differentiate among groups of countries with access to the most efficient solar plants and/or less opposition to new nuclear power plants that would lead to lowest DAC operations cost and the other countries. In the latter group, we find only USA and European countries. Those figures are in line with the estimates of the literature. The levelized cost computed by Keith et al. [21] is 232\$/t-CO_2 captured, whereas the APS study proposed a levelized cost of 550\$/t-CO_2. In [16] the cost for powering a DAC plant using a natural gas-fired plant with CCS was 396\$/t-CO_2 avoided. The extra energy cost of DAC was estimated around 232\$/t-CO_2 captured, based on [27]. The storage cost has been evaluated in [42] to be in the range of 6 to 13\$/t-CO_2 stored.

Regarding BECCS, we consider the standard technology that consists in producing electricity from biomass while capturing and injecting CO_2 into geological formations. We use a unique worldwide levelized cost of 60\$/t-CO_2 which is consistent with the IEA estimates [23].

4.2.2 DAC and BECCS potentials

The total quantity of CO_2 captured by DAC and other carbon capture technologies will be constrained by the potential of CO_2 storage in the different groups of countries considered in this paper. Estimates of these storage potentials, including deep saline aquifers, hydrocarbon fields and coal beds are derived from [28]. We assume that only 25% of these potentials can be used for DAC and BECCS technologies by 2100, as reported in Table 2. We also assume that these technologies will be mature enough for massive deployment in 2040 with a linear deployment trend afterwards.

Table 2: Carbon storage potential per region in Gt CO_2

United States of America	24.0
European Union	37.5
China	30.5
India	20.0
Russia	126.5
Gulf Cooperation Council	86.0
Other energy exporting countries	23.0
Rest of asian countries	46.0
Latin America	40.5
Rest of the World	23.0
World	447.0

In addition to storage capacities, BECCS potentials can also be constrained in some countries by limited access to biomass, which in particular the case for Gulf countries. We calibrate those potentials of biomass based on the average of Shared Socioeconomic Pathways simulations [37].

5 Simulation results and design of fair climate agreements

5.1 The business as usual scenario

Our BAU scenario is computed by GEMINI-E3 from 2017 to 2050 and is calibrated mainly from the World Energy Outlook 2016 [18] and more specifically on the “New Policies” scenario. After 2050, we use the protocol described in Section 4 to derive the BAU figures from 2050 to 2100. The demographic assumptions are based on the “median variant” scenario done by United Nations [48]. The parameters ν^1 and ν^2 equal respectively 0.01 and -0.01. The Figure 2 shows the population, the GDP and the resulting CO_2 emissions at worldwide level in the BAU scenario. World population increases by 50% from 2016 to 2100 and reaches 11.2 billion of inhabitants in 2100. On the same period, global GDP is multiplied by 7 representing a 2.4% annual growth rate. In our BAU scenario, global CO_2 emissions reach a maximum of 48.3 billion tons of CO_2 in 2070, and then decrease up to 46.8 billion tons of CO_2 at the end of our century. This emissions decline can be interpreted by the rarefaction of fossil energies in the second part of the 21st century. According to our BAU scenario, more than 4'107 Gt of CO_2 will be emitted during the 21st and 6'327 Gt of CO_2 from 1876 to the end of our century. That represents more than 3.5°C surface temperature change since 1850-1900 with at least 66% probability[4].

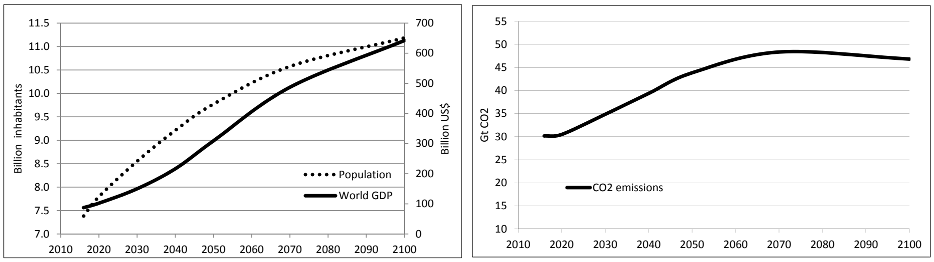


Figure 2: Population, GDP and CO_2 emissions in the BAU scenario at World level

5.2 Mitigation scenarios

5.2.1 Global figures

Figure 3 shows the global trajectory of CO_2 emissions and net emissions without and with DAC/BECCS. Net emissions are equal to CO_2 emissions minus the sequestered emissions from DAC and BECCS. Table 3 gives the CO_2 price and the worldwide welfare cost. Without CO_2 sequestration more abatement are required and CO_2 emissions have to converge to zero level at the end of the 21st century. The welfare cost are significant and is equal to 3.7% of the discounted GDP with a CO_2 price equal to 369$ in 2020. When DAC and BECSS are used, the worldwide welfare cost is reduced to 2.3% and the CO_2 price equals 218$ (assuming a 3% discount factor). CDR contribute to the CO_2 mitigation mostly in the second part of 21st century as it can be seeing in the net emissions trajectories. With DAC and BECCS, our results are consistent with the figures of the mitigation scenarios given in the special report of Global Warming of 1.5°C done by IPCC [40]. Indeed, within a 2°C mitigation pathway with greater than 66% likelihood, IPCC

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[4] See Figure 2.3 in [40].

reports a median value of carbon price discounted at a 5% discount rate to 2020 equal to 75\$ per ton of CO$_2$[5]. With a scenario using a 5% discount factor, we find a 113\$ CO$_2$ price (see Table 3).

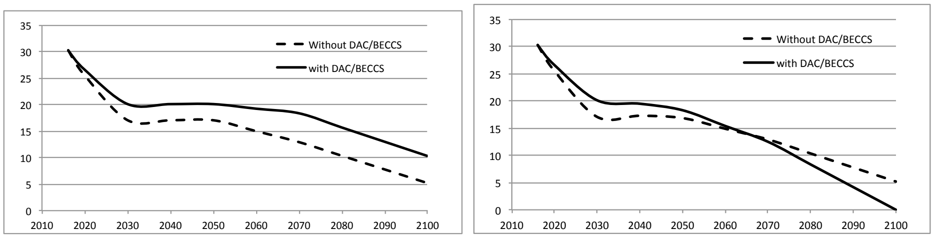

Figure 3: Emissions (left) and net emissions (right) trajectories in Gt CO$_2$ at World level

Table 3: CO$_2$ price and welfare cost

	Without DAC & BECCS	With DAC & BECCS	
Budget in Gt CO$_2$	1170	1170	1170
Discount factor	3%	3%	5%
Discounted CO$_2$ price in 2020 in \$$_{2010}$	369	218	113
Discounted World cost in % of discounted GDP	3.7%	2.3%	1.7%

Figure 4 shows the contribution of DAC and BECSS in the mitigation scenarios. We compute the variation of global welfare cost as a function of the size of the global carbon budget (see Figure 5). The diagram shows that the 1.5°C objective appears to be very challenging [41, 32], with a cost multiplied by a factor of 3.6.

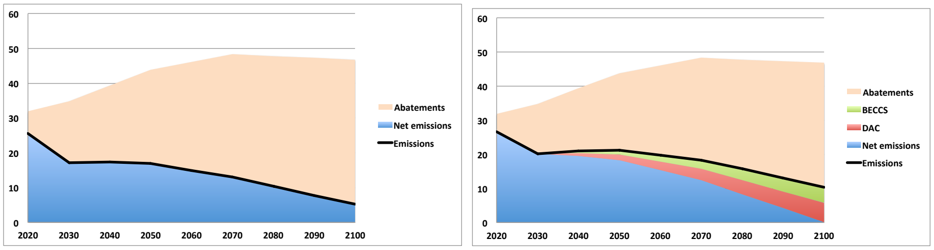

Figure 4: Net emissions, DAC, BECCS and abatement profiles without and with DAC/BECCS in Gt CO$_2$

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[5] See Figure 2.26, page 153 in [40].

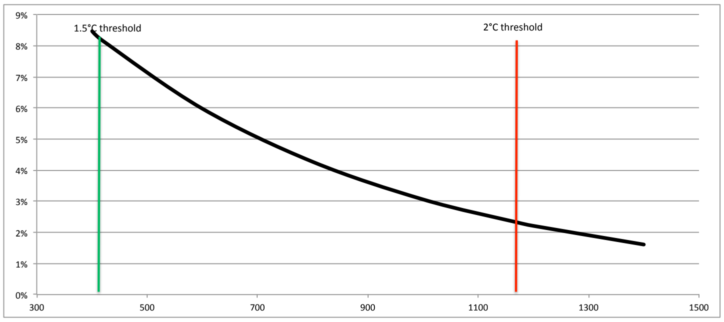

Figure 5: Discounted global welfare cost in % of discounted GDP with respect to carbon budget in Gt CO_2

5.2.2 Designing fair burden-sharing agreements

In this section, we analyse how to allocate the carbon budget in a fair manner. Global climate justice is a thorny issue (see the recent survey [35]) and several different fairness criteria can be invoked. First, we use two common rules that have been extensively analysed in the literature: Grandfathering and equal individual emission rights (Per Capita). Table 4 gives the results of these two allocations.

The first rule considers that the allocation of quotas is proportional to emissions on the whole period (i.e. 2016-2100) in the BAU scenario. This sovereignty principle is usually proposed as a starting point in environmental negotiations taking into account the existing situations. Energy exporting countries (Russia, GCC countries and OEE) and rest of the World support a very high burden whereas India, Latin America and China benefit largely from this allocation.

The second rule assumes that the budget share is proportional to the population over the period 2016-2100. This equalitarian rule gives a large number of extreme welfare impacts. The most populated countries earn significant revenues coming from emissions selling. Therefore, India, rest of the World and Latin America experience welfare improvement after implementing the climate mitigation policy. In contrast, energy exporting countries but also China and USA bear a huge welfare cost.

We now design a burden-sharing rule that equalizes the welfare loss among the countries and group of countries. We name this rule “Rawlsian” allocation. Table 5 shows the results of this game. It is interesting to compare this burden-sharing with the ones computed from grandfathering and per capital rules. With this allocation, energy exporting countries receive

Table 4: Burden-sharing and welfare cost with grandfathering and per capita rules

	Grandfathering		Per capita	
	Budget share	Welfare cost[a]	Budget share	Welfare cost[a]
United States of America	13.6%	1.4%	4.0%	3.9%
European Union	7.7%	2.1%	4.2%	3.0%
China	24.8%	0.9%	12.8%	4.4%
India	9.0%	0.1%	16.0%	-5.9%
Russia	3.3%	2.7%	1.3%	6.5%
Gulf Cooperation Council	3.7%	10.4%	0.8%	18.9%
Other energy exporting countries	10.9%	4.3%	12.9%	3.6%
Rest of asian countries	13.0%	2.2%	16.8%	1.4%
Latin America	2.9%	0.8%	4.4%	-1.2%
Rest of the World	11.1%	5.3%	27.0%	-2.9%
World	100.0%	2.3%	100.0%	2.3%

[a] Discounted welfare cost in % of discounted GDP

significant allocations to counterbalance their loss in terms of trade. USA, Europe, China and rest of the world have allocations that are between the grandfathering and per capita rules. In contrary, India, rest of asian countries and Latin America receive less quotas than the ones computed from grandfathering and per capita rules. Table 5 gives also the components of the welfare cost. They confirm that energy exporting countries suffer from huge loss of terms of trade. In contrary they receive significant revenue coming from emissions trading. Regarding abatement costs, DAC and BECSS are relatively low cost abatement options in comparison to "traditional" CO_2 emissions abatement. There is an exception in Russia and GCC countries where the huge amounts of air captured induce high cost of abatement (i.e. 3%).

Figure 6 shows the contribution of each mitigation options at worldwide level. DAC and BECSS represent 18% of the global abatement.

Table 5: Burden-sharing and welfare cost with Rawlsian rule

	Budget	Welfare	Components of welfare cost^a				
	share	cost^a	Abatement	DAC	BECCS	GTT	Exchange
United States of America	10.16%	2.32%	1.86%	0.11%	0.04%	-0.01%	0.32%
European Union	6.75%	2.32%	0.79%	0.18%	0.04%	-0.46%	1.78%
China	19.84%	2.32%	3.72%	0.11%	0.03%	-0.66%	-0.87%
India	6.34%	2.32%	3.40%	0.19%	0.08%	-1.37%	0.02%
Russia	3.51%	2.32%	3.19%	2.48%	0.25%	2.01%	-5.60%
Gulf Cooperation Council	5.78%	2.32%	3.26%	2.42%	0.04%	5.69%	-9.08%
Other energy exporting countries	16.69%	2.32%	1.73%	0.12%	0.03%	1.05%	-0.60%
Rest of asian countries	12.30%	2.32%	1.42%	0.12%	0.03%	-0.72%	1.48%
Latin America	1.69%	2.32%	1.83%	0.79%	0.19%	0.13%	-0.62%
Rest of the World	16.93%	2.32%	2.59%	0.17%	0.04%	0.34%	-0.82%
World	100.0%	2.32%	2.05%	0.26%	0.05%	0.00%	0.00%

[a] Discounted welfare cost in % of discounted GDP

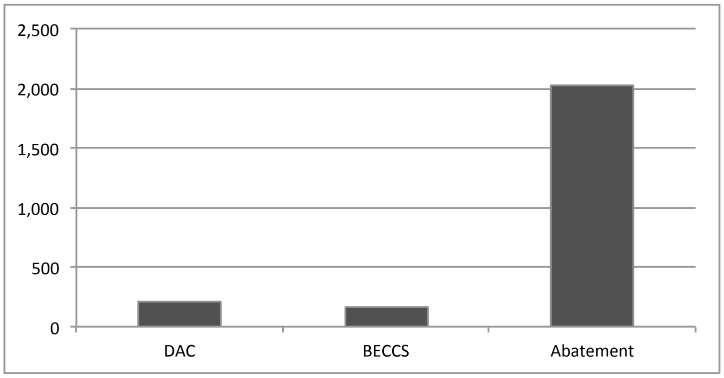

Figure 6: Worldwide contribution of mitigation options in Gt CO_2

6 Conclusion

A dynamic meta-game model used to assess the future of Paris agreement has been extended to bear on the whole 21^{st} century and to include the use of CDR technologies as strategic variables. This has required to extend the GEMINI-E3 model to cover also the second half of the 21^{st} century and allow computation of representative abatement cost functions. A fair sharing of the safety cumulative emissions budget has been proposed, in which the potential for implementing DAC activities in GCC countries plays an important role. Indeed by allowing natural gas to be used to capture CO_2 in the atmosphere with storage in depleted reservoirs, on creates a new resource with very low logistical cost which is sold on the financial market. This indicates the need to take into considerations CDR technologie, and DAC technologies in particular in the assessment of future climate negotiations. This paper is a step in that direction, complementing, via the use of macroeconomic general equilibrium model, the work reported in [10, 49, 28] which were based on integrated assessment models. Further research is needed to include also other CDR technologies that could contribute to reaching a net-zero emission regime. Indeed, sensitivity analysis and/or robustification of equilibrium computation should be also developed.

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