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An oligopoly game of CDR strategy deployment in a steady-state net-zero emission climate regime

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Abstract: In this paper, we propose a simple oligopoly game model to represent the interactions between coalitions of countries in deploying Carbon Dioxide Removal (CDR) strategies in a steady-state net-zero emission climate regime that could take place by the end of the 21st century. The emission quotas and CDR activities obtained in the solution of this steady-state model could then be used as a target for end-of-period conditions in a dynamic integrated assessment analysis studying the transition to 2100. More precisely, we analyze a steady-state situation where m coalitions exist and behave as m players in a game of supplying emission rights on an international emission trading system. The quotas supplied by a coalition must correspond to the amount of CO₂ captured through CDR activities in the corresponding world region. We use an extension of the computable general equilibrium model GEMINI-E3 to calibrate the payoff functions and compute an equilibrium solution in the noncooperative game.

Keywords: Carbon dioxide removal, climate change, integrated assessment, mitigation, negative emissions, steady-state game

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1 Introduction

In a report published in 2016 [45], Shell Corp. declared:

“In spite of the many challenges, the practical details of providing enough energy for a better life for everyone with net-zero emissions can be envisaged, and that is reassuring, even inspiring.”

This report has been updated in 2018 in the energy transition ‘Sky’ scenario where net-zero emissions are envisaged as soon as 2070 [46]. The UNFCCC Paris Agreement, negotiated at COP-21 and signed by a majority of nations, is dedicated to limiting to less than 2°C the surface average temperature (SAT) rise in the 21st century. To achieve this goal, the participating countries must reduce their emissions of greenhouse gases (GHG) mostly related to the use of fossil energy as an economic production factor. Recent results from climate modeling tend to show that to limit the SAT rise to 2°C with sufficiently high probability, one should define a global limiting carbon budget of about 1 trillion tons over the whole period starting from the Industrial Revolution to the end of the 21st century [1, 30]. After this period the world economy should stay with a ‘net-zero emission’ regime. In such a regime, there will still be technologies emitting GHGs. However these emissions should be offset by ‘negative emissions’ obtained somewhere on the planet.

As in the Shell Sky scenario, most of the studies assessing climate policies that would be compatible with the Paris Agreement propose a path to a net-zero or even net-negative emission regime; see for instance [42]. Carbon dioxide removal (CDR) strategies, which reduce the level of carbon dioxide in the atmosphere may be used to achieve negative emissions [17]. Among such strategies one finds in particular afforestation, bioenergy with carbon capture and storage (BECCS), and direct air carbon capture and storage (DACCS) [21, 33, 34, 50]. The deployment over time of CDR approaches can be analyzed using integrated assessment models (IAMs). In many policy simulations performed with IAMs, 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 allowing reaching a net-zero emission regime around 2070;¹ see e.g. [2, 15, 25, 31, 32, 34, 38, 39, 49, 52].

However, IAMs used to produce transition pathways to net-zero emissions typically omit to specify the end-of-period conditions that should prevail in order to maintain a net-zero emission regime in a sustainable economy. The contribution of this paper is to formulate a net-zero emission climate regime, in steady-state, with several groups (coalitions) of countries, which will use strategically the deployment of CDR strategies to supply emission quotas on an international carbon market. The concept of a steady-state model to study the competition among regions producing negative emissions has been proposed in [11], where the steady-state was representing the long-term attractor (turnpike) in an optimal economic growth model with two types of economies as described in [10]. In the present paper, we use a computable general equilibrium (CGE) model GEMINI-E3, extended to represent a possible world economy at the end of 21st century, to evaluate abatement costs and changes in terms of trade, for 11 groups of countries. Particular attention is also given to the representation of costs and potentials for three CDR strategies, namely, afforestation (AFF), BECCS, and DACCS. In order to foster economic efficiency, an international emission trading scheme could be established where each coalition of countries has an endowment in emission rights which corresponds exactly to the level of negative emissions obtained in this coalition. Then, the coalitions use their emission rights in a strategic way, in order to extract the most welfare benefits, taking into consideration the actions of the other countries that intervene on the international carbon market (see [23] for a discussion of the strategic use of allowances). This corresponds broadly to an oligopoly competition model.

The paper is organized as follows. In Section 2, we justify the development of a steady-state model and we present the equations of the oligopoly game model. In Section 3, we explicit how the payoff functions and the constraints in this game have been calibrated using statistical emulation of an

¹Actually, several world regions (for instance Canada, or the European Union through its European Green Deal) are aiming to reach carbon neutrality as early as 2050.

extended version of the CGE model GEMINI-E3. In Section 4, we analyze a ‘nominal’ Nash equilibrium solution where the coalitions compete on an international emission trading system, corresponding to a set of representative nominal values for the techno-economic parameters of the model. In Section 5, we perform sensitivity analysis and explore different scenarios using this oligopoly model. Finally, we conclude in Section 6 and propose an agenda for further research.

2 A Steady-state oligopoly game model

2.1 The case for a steady-state model

Most of the integrated assessment models developed to tackle the climate change issue have been dynamic models designed to explore the path toward achieving long-term sustainability goals. For example, in a recent development [5] the path toward the attainment of the Paris Agreement objectives has been evaluated, and a possibility to achieve a fair burden sharing through allocations of shares of a limited cumulative emission budget to different groups of countries has been assessed. A recent IPCC report [43] presents several emission trajectories proposed by different integrated assessment models to abide to the Paris Agreement objectives. They all consider a very stringent abatement trajectory reaching net-zero emissions before the end of the century. When a net-zero emission regime is attained, the only emissions that should be allowed are those that are compensated by a CDR activity.

We consider a situation at the end of the 21st century or beyond, where development goals in different regions of the world have been achieved. To represent a ‘sustainable world’ we use an economic model in steady state. Therefore a steady-state oligopoly game could be formulated to represent the competition among different regions in the supply of emissions quotas via CDR activities.

2.2 Alternative CDR strategies

Beyond afforestation, an approach of choice to produce negative emissions is BECCS [2, 3, 41, 44]. However this approach is not without risks and limitations, related in particular to the amount of arable land needed to grow energy crops [24]. Another alternative is direct air carbon capture (DAC). It involves the chemical sorption of dilute CO₂ from flowing air and the release of concentrated CO₂ while regenerating these chemicals.² DAC is, however, ineffective if the CO₂ emissions associated with the energy to run the capture plant become comparable to the quantities of CO₂ 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 CO₂ from these facilities. Other approaches would use non-carbon (renewable or nuclear) energy sources. In principle, any concentrated stream of CO₂ produced by DAC or industrial CO₂ capture could be recycled into ‘low-carbon’ fuels, such as ‘low-carbon diesel’. Here, we rather consider DACCS, where the CO₂ captured from both the local energy production plants and the DAC facilities is stored.

The potential for implementing DACCS is expected to vary considerably among world regions. The first criterion to assess this potential 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., in depleted oil and gas reservoirs, aquifers, etc.). Moreover, DACCS technologies might be quite expensive. Current assessments envision a cost between \$200 and \$600 USD per ton of CO₂ removed [15, 24, 29, 32]. Besides, 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 DACCS 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 [12] will, in the future, obtain a negative emission rent through the implementation of large-scale DACCS systems.

²See the APS report [48].

2.3 Model assumptions and equations

Assume a world economy in steady-state with several coalitions that regroup countries with similar macroeconomic structure. Each coalition is characterized by its baseline (BAU) GHG emissions, which would occur under minimal climate policies, and an abatement cost function, which describes the burden for achieving additional emission reductions. The coalitions supply permits on a carbon market, using strategically their development of CDR activities (AFF, BECCS, and DACCS) to generate negative emissions. We consider 11 coalitions³ of countries/regions that are listed in Table 1.

Table 1: Coalitions of countries/regions in the model

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

Variables and parameters

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

$k \in \{1, \dots, \kappa\}$: index of CDR strategies;

ν_j : K-T multiplier for quotas budget constraint of coalition j ;

ω_j : supply of emission quotas by coalition;

Ω : total supply of emission permits;

v_j : total negative emission activity (CDR) by coalition j ;

$v_{j,k}$: negative emission activity (CDR) by strategy k in coalition j ;

$v_{j,\cdot}$: vector of negative emission activities (CDR) in coalition j ;

λ_j : multiplier for CCS bound constraint;

$\kappa_j(v_j)$: cost of CDR for coalition j ;

q_j : abatement level by coalition j ;

ϵ_j : BAU emission level by coalition j ;

e_j : emission level by coalition j ;

\mathbf{e} : vector of all m emission levels ;

$\varpi_j(\mathbf{e})$: Net abatement cost (including changes in the terms of trade) for coalition j ;

$\gamma_j(\sum_{i=1}^m q_k)$: gains from the changes in terms of trade for coalition j ;

$\Phi_{j,k}(v_{j,k})$: levelized cost for level $v_{j,k}$ of activity k in coalition j ;

$UB_{j,k}$: upper-bound for level $v_{j,k}$ of activity k in coalition j ;

$CCSB_j$: upper-bound for carbon capture and sequestration in coalition j ;

$rCCSCDR_{jk}$: ratio of CCS to CDR activity;

$c_{j,k}$: linear coefficient in cost for level $v_{j,k}$ of activity k in coalition j ;

α_{jk} : scaling parameter in cost function of CDR activity k in coalition j .

³We distinguish Qatar and other Gulf Cooperation Council (GCC) countries, as this study is part of a research project supported by the Qatar National Research Fund.

Emissions from abatement

Abatement and emission levels relative to BAU relate as follows

$$e_j = \epsilon_j - q_j. \quad (1)$$

Quotas supply constraints

The quotas supplied by coalition j are equal to the negative emissions generated by the coalition.

$$v_j - \omega_j \geq 0. \quad (2)$$

Emissions trading

An international carbon market determines a price and emission levels. The market equilibrium conditions are

$$p = \frac{\partial}{\partial q_j} \varpi_j(q_j); \quad j = 1, \dots, m, \quad (3)$$

$$\Omega = \sum_{k=1}^m e_k; \quad j = 1, \dots, m. \quad (4)$$

The price and emission levels are functions of the total permit supply Ω , thus denoted $\tilde{e}(\Omega)$ and $\tilde{p}(\Omega)$, respectively. As shown in Helm [23], the derivatives w.r.t. Ω of price and emission levels are given by

$$\tilde{p}'(\Omega) = \frac{1}{\sum_{j=1}^m \frac{1}{\frac{\partial^2 \varpi_j(q_j)}{\partial q_j^2}}} \quad (5)$$

$$\tilde{e}'_j(\Omega) = \frac{1}{\sum_{i=1}^m \frac{\frac{\partial^2 \varpi_j(q_j)}{\partial q_j^2}}{\frac{\partial^2 \varpi_j(q_i)}{\partial q_i^2}}} \quad (6)$$

CDR cost function

We assume that each CDR strategy has a cost function which begins as linear, with unit cost $c_{j,k}$, and is complemented by a cost which grows to infinity as the activity level tends to the upper limit $UB_{j,k}$, as shown in (7)

$$\Phi_{j,k}(v_{j,k}) = c_{j,k}v_{j,k} + \alpha_{j,k} \frac{UB_{j,k}}{UB_{j,k} - v_{j,k}}, \quad \forall j, k \quad (7)$$

where $\alpha_{j,k}$ is a scaling factor.

Bounds on CCS capacity

Each region j has a storage capacity (in tons/year) for captured CO_2 defined by parameter $CCSB_j$. When capturing one ton of CO_2 in the air, activity k in region j has to sequester $rCCSCDR_{jk}$ tons of CO_2 , since eventual GHG emissions from the energy source must also be stored. This ratio could be close to 1 if the energy source is renewable, 0 if dealing with afforestation, more than 1 if the energy source is a fossil fuel. The corresponding equation is

$$CCSB_j - \sum_k rCCSCDR_{jk} \times v_{j,k} \geq 0, \quad \forall j. \quad (8)$$

Payoffs

The net cost to coalition j includes the abatement cost, plus the cost of buying permits on the market (negative if selling), plus the one associated with CDR activities (investment and levelized

cost). We assume that the supply of permits and CDR activities of each coalition is strategically defined as the Nash equilibrium for the game with payoffs (9) and constraints (2). Notice that carbon price p , emission levels e_j and, consequently abatement levels q_j , are determined by the carbon market equilibrium conditions (3)–(4), as functions of the total supply of quotas Ω ,

$$\psi_j(\omega_j, \Omega, v_{j,\cdot}) = p(\Omega)(\omega_j - e_j(\Omega)) + \gamma_j \left(\sum_i q_i(\Omega) \right) - \varpi_j(q_j(\Omega)) - \sum_k \Phi_{j,k}(v_{j,k}), \quad \forall j. \quad (9)$$

2.4 Computing a steady-state Nash equilibrium

We assume that an international emission trading scheme is implemented. In a steady-state net-zero emission regime, the total supply of emission permits should be equal to the amount of negative emissions obtained through the use of CDR activities. Each coalition, considered as a ‘big’ player j , may then use the supply of emission permits on the carbon market as a strategic variable in order to maximize returns from the negative emissions they control. The other strategic variables are the CRD levels. A Nash equilibrium is obtained when each coalition has chosen its strategy as a best reply to the choices made by the other coalitions. A strategy \bar{s}_j for coalition j consists more precisely of:

- an activity level for each CDR strategy available defining the vector $v_{j,\cdot}$;
- an amount of emission rights ω_j supplied on the carbon market.

As indicated in Equation (2), the supply of emission rights by coalition j must be equal to the negative emissions produced by this coalition. Market clearing conditions determine the price of emission rights and the emission levels in each coalition. To compute a Nash equilibrium, we formulate the model as a nonlinear complementarity problem and solve it using the PATH solver [19].

Complementarity conditions on Lagrangian pseudogradients

For each coalition j we define the Lagrangian

$$\begin{aligned} \mathcal{L}_j(\omega_j, \Omega, v_{j,\cdot}, \nu_j) &= p(\Omega)(\omega_j - e_j(\Omega)) \\ &+ \gamma_j \left(\sum_i q_i(\Omega) \right) - \varpi_j(q_j(\Omega)) - \sum_k \Phi_{j,k}(v_{j,k}) + \nu_j(v_j - \omega_j) \\ &+ \lambda_j(CCSCB_j - \sum_k rCCSCDR_{jk} \times v_{j,k}), \end{aligned} \quad (10)$$

where $v_j = \sum_k v_{j,k}$. The gradient w.r.t. ω_j is given by

$$\frac{\partial \mathcal{L}_j}{\partial \omega_j} = p(\Omega) - p(\Omega)e'_j(\Omega) + p'(\Omega)(\omega_j - e_j(\Omega)) - \gamma'_j \left(\sum_i q_i(\Omega) \right) \sum_i e'_i(\Omega) + \varpi'_j(q_j(\Omega)e'_j(\Omega) - \nu_j). \quad (11)$$

Since $p(\Omega) = \varpi'_j(q_j(\Omega))$ by market equilibrium condition (3), and since $\sum_i e'_i(\Omega) = 1$ by market equilibrium condition (4), the gradient expression simplifies as

$$\frac{\partial \mathcal{L}_j}{\partial \omega_j} = \varpi'_j(q_j(\Omega)) + p'(\Omega)(\omega_j - e_j(\Omega)) - \gamma'_j \left(\sum_i q_i(\Omega) \right) - \nu_j. \quad (12)$$

The gradient w.r.t. $v_{j,k}$ is given by

$$\frac{\partial \mathcal{L}_j}{\partial v_{j,k}} = \nu_j - \Phi'_{j,k}(v_{j,k}) - \lambda_j \times rCCSCDR_{jk}. \quad (13)$$

The complementarity conditions for a Nash equilibrium are therefore

$$\begin{aligned} -\frac{\partial \mathcal{L}_j}{\partial \omega_j} &\geq 0 & j = 1, \dots, m \\ \omega_j &\geq 0 & j = 1, \dots, m \end{aligned}$$

$$\begin{aligned}
\frac{\partial \mathcal{L}_j}{\partial \omega_j} \omega_j &= 0 & j &= 1, \dots, m \\
-\frac{\partial \mathcal{L}_j}{\partial v_{j,k}} &\geq 0 & j &= 1, \dots, m \\
& & k &= 1, \dots, \kappa \\
v_{j,k} &\geq 0 & j &= 1, \dots, m \\
& & k &= 1, \dots, \kappa \\
\frac{\partial \mathcal{L}_j}{\partial v_{j,k}} v_{j,k} &= 0 & j &= 1, \dots, m \\
& & k &= 1, \dots, \kappa \\
v_j - \omega_j &\geq 0 & j &= 1, \dots, m \\
\nu_j &\geq 0 & j &= 1, \dots, m \\
\nu_j(v_j - \omega_j) &= 0 & j &= 1, \dots, m \\
CCSB_j - \sum_k rCCSCDR_{jk} \times v_{j,k} &\geq 0 & j &= 1, \dots, m \\
\lambda_j(CCSB_j - \sum_k rCCSCDR_{jk} \times v_{j,k}) &= 0 & j &= 1, \dots, m.
\end{aligned}$$

3 Model calibration

The oligopoly model sketched above is relatively simple, but the payoff and constraint parameters are obtained from an extrapolation of a detailed world general equilibrium model that used to perform a meta-modeling exercise through statistical emulation. This approach has been used in several papers dealing with the burden sharing issue in the assessment of climate policy agreements [5, 6, 7, 8, 9, 22].

3.1 The GEMINI-E3 model

To calibrate the oligopoly model one uses GEMINI-E3, a worldwide multi-country multi-sector CGE model specifically designed to assess energy and climate change policies [13, 14]. The version used in this paper describes the 11 countries/regions presented in Table 1 and 11 sectors. The standard model is based on the assumption of total flexibility in all markets, i.e., both macroeconomic markets, such as capital and international trade markets (with associated prices being the real rate of interest and the real exchange rate, which are then endogenous), and microeconomic or sector markets (goods, factors of production, etc.). For each sector, the model computes the demand from its production on the basis of household consumption, government consumption, exports, investments and intermediate uses. Total demand is then divided between domestic production and imports using the Armington assumption, which assumes that domestic and imported goods are not perfectly homogenous. Production technologies are described by a nested Constant Elasticity of Substitution (CES) functions. Households behavior consists of three interdependent decisions: (1) labor supply; (2) savings; and (3) consumption of the various goods and services. In this version, we suppose that both labor supply and the rate of savings are exogenous. Demand for the different commodities has prices of consumption and income (more precisely ‘spent’ income, income after savings) as arguments, and is derived from a nested CES utility function. The government collects taxes and distributes the resulting revenues to households and firms through transfers and subsidies. Wage is chosen as a numeraire in each region. The model is recursive dynamic, with backward looking (adaptive) expectations. Energy consumption by firms and households is computed in physical quantities and differentiate coal, refined oil, natural gas and electricity. Based on these energy consumptions the model computes CO₂ from energy combustion. The model database is based on GTAP 9 [37], therefore all monetary values reported in this paper are in 2011 USD.

3.2 Baseline CO₂ emissions

To calibrate the steady-state game, we first use the model to compute CO₂ emissions and main macroeconomic variables for a baseline (BAU) scenario in which we assume implementation of limited climate policies. Since the time span of GEMINI-E3 is limited to the first half of our century (i.e., up to 2050), we have implemented a procedure to extend the horizon to 2100 and assuming that an economic steady state is reached at the end of the century. First, we select a demographic scenario among the projections done by the United Nations [51] and determine the working population⁴ $pop_j(t)$. 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 CO₂ emissions per GDP, $e_j(t)/gdp_j(t)$, decrease with an annual rate that converges to a single value ν^2 . We can thus simulate various BAU scenarios by setting a value for the three parameters defined above (demographic scenario, ν^1 and ν^2). This is summarized by the following equations

$$\begin{aligned}
 \frac{gdp_j(t) - gdp_j(t-1)}{gdp_j(t-1)} &= \frac{pop_j(t) - pop_j(t-1)}{pop_j(t-1)} (1 + \nu_j^1(t))^{\delta(t)} \\
 \frac{e_j(t) - e_j(t-1)}{e_j(t-1)} &= \frac{gdp_j(t) - gdp_j(t-1)}{gdp_j(t-1)} (1 + \nu_j^2(t))^{\delta(t)} \\
 \nu_j^1(t) &= \nu_j^1(t-1) - \delta(t)(\nu_j^1(t-1) - \nu_j^1(T))/(\delta(T-1) + \delta(T)) \\
 \nu_j^2(t) &= \nu_j^2(t-1) - \delta(t)(\nu_j^2(t-1) - \nu_j^2(T))/(\delta(T-1) + \delta(T)) \\
 \nu_j^1(T) &= \nu^1 \quad \forall j \\
 \nu_j^2(T) &= \nu^2 \quad \forall j
 \end{aligned} \tag{14}$$

The steady-state regime chosen corresponds to the 2100 figures calibrated from GEMINI-E3 with its versatile macroeconomic representation. Taking into consideration three demographic scenarios and assuming that parameters ν_j^1 and ν_j^2 in Equation (14) are equal respectively to 1% and -1%, we obtain three different steady-state worlds that are summarized in Table 2.

In medium and high scenarios, CO₂ emissions will be above the current level (33.2 Gt CO₂ in 2018 according to [27]) by 40% and 109%, respectively. Conversely, in the low scenario, carbon emissions would be 12% lower due to lower economic growth.

Table 2: Steady-state world

	Demographic scenarios		
	Low	Medium	High
Population in billions of inhabitants	7.3	11.2	16.5
World GDP [Trillions USD 2011 [†]]	400	642	954
CO ₂ emissions [GtCO ₂ /yr]	29	47	69

[†] using market exchange rate

Figure 1 shows the contribution of each region in global CO₂ emissions for the three demographic scenarios. China is the highest CO₂ emitter with a share ranging between 18% (low scenario) and 22% (high scenario), followed by USA (14% to 13%), India (8% to 9%). The other significant emitters are OEE (13% to 16%), ROW (17% to 14%) and ASI (12% to 13%).

Let us now compare our three demographics scenarios and the resulting GDP and CO₂ emissions with the Shared Socioeconomic Pathways (SSP) [40]. Our low demographic scenario is close to the SSP1 scenario (called *Sustainability – Taking the Green Road*) with a global population reaching 7 billion of inhabitants in 2100, compared to 7.3 in our low demographic scenario. Global GDP and CO₂ emissions are also within the range of the SSP1 scenario. Population and CO₂ emissions in our medium scenario are between the SSP3 and SSP4 pathways, but our resulting GDP is above the one computed by the two SSP scenarios. Finally, our high demographic scenario (where global population reaches

⁴Male and female population aged from 20 to 64.

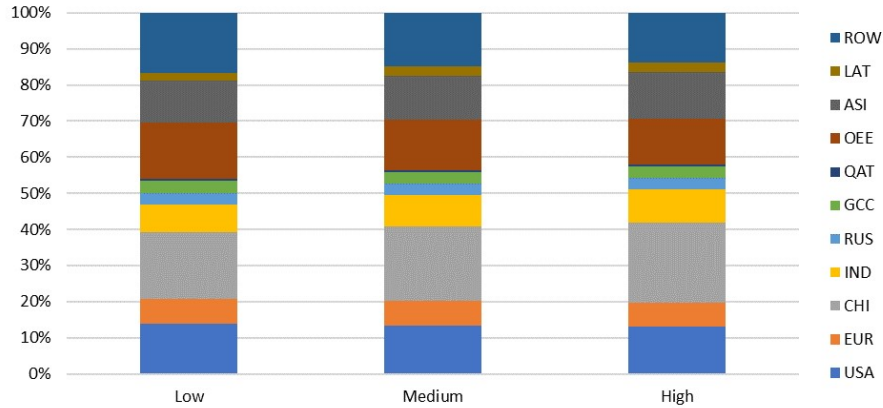


Figure 1: Regional CO₂ in percentage

16.5 billion in 2100) is outside the range of the SSPs, where the highest level reached is 12.6 billion (in SSP3). However, CO₂ emissions (that reach 69 GtCO₂ in 2100) have a similar level than in SSP2. Our global CO₂ emissions⁵ in 2100 vary thus between 29 and 69 Gt CO₂, while SSP pathways present higher emissions (in SSP5). The latter scenario corresponds to an energy and resource intensive scenario with a tripling of energy demand over the 21st century and about a third more of CO₂ emissions (compared to our high demographic scenario).

3.3 Marginal abatement cost and changes in the terms of trade functions

GEMINI-E3 is used to calibrate the payoff functions (π_j) in the game through a statistical emulation approach, as explained in [8]. In short, various climate policies are simulated by GEMINI-E3, and we perform econometric estimations of the domestic abatement cost $\varpi_j(q_j)$ and gains from terms of trade $\gamma_j(\sum_{k=1}^m q_k)$ functions. The gains in the terms of trade (GTT) represent spillover effects due to changes in international prices [13]. In a climate change policy, these GTTs come mainly from the drop in fossil energy prices that result from the decrease of world energy demand. The Marginal Abatement Cost (MAC) functions, calibrated as indicated above, are polynomials of degree 3.

$$\varpi_j(q_j) = a_{1j}q_j + a_{2j}q_j^2 + a_{3j}q_j^3 \quad (15)$$

They are estimated for the year 2050 as shown in Figure 2. Abatement functions $\varpi_j(q_j)$ are then extrapolated for the year 2100 by assuming an annual technical progress in abatement technologies (called ν_j^3) that decreases the cost of abatement. We use a rather pessimist assumption, where ν_j^3 is equal to 0.3% per year. A sensitivity analysis performed in Section 5 considers more optimistic values on this technical progress. GTT functions $\gamma_j(\sum_{k=1}^m q_k)$ in 2100 are supposed unchanged with respect to 2050 figures.

3.4 Potentials and costs of CDR strategies

We acknowledge it is difficult to estimate the potentials and costs of Afforestation, BECCS and DACCS for the end of the 21st century. The approach we have adopted is to devise ‘nominal’ values by extrapolating most recent estimates proposed in the literature for 2050. These values will be used to produce a ‘nominal’ baseline scenario, which will be complemented by robustification and sensitivity analysis procedures. These nominal values are given in Table 3, below.

Bounds on CO₂ storage via CCS have been estimated from [28]. We use their lower estimates on total storage that include onshore and ‘practical’ offshore storage. Our steady-state CO₂ storage

⁵Emissions from energy combustion.

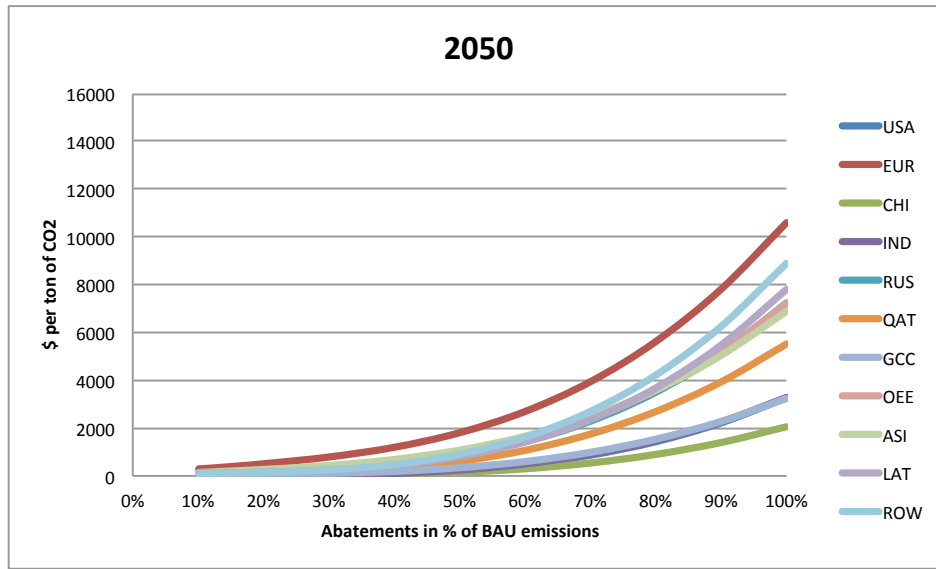


Figure 2: Marginal abatement cost in 2050

potential is equal to 1% of their storage potential, namely 79 Gt CO₂ per year. This potential has to be shared between BECCS and DACSS activities.

Potentials on afforestation are calibrated from [18], where CO₂ sequestered by forest was computed using a forest optimization model. We estimate the global sequestration by forest to be 4 GtCO₂, a slightly conservative value with respect to the 5.8 GtCO₂ in 2100 computed by [16]. Moreover, we use a nominal cost value of 20 \$/tCO₂ captured through afforestation, following [20] that reports on a cost range of 5-50 \$/tCO₂ captured in 2050.

Potentials of CO₂ capture through BECCS are estimated from [26], namely, a global level of 8.2 GtCO₂ following a 2050 technical potential. This figure takes into account biomass supply chains and processing, as well as deployment issues in terms of policy and regulatory barriers. This potential can be considered as rather conservative for 2100, as one expects a stronger penetration of bioenergy by then. The cost of implementing BECCS is also quite uncertain. Based on a literature review, [20] proposes a cost range of 100-200 \$/tCO₂ captured in 2050. Assuming that technological progress will continue after 2050, we have chosen a lower nominal value of 60 \$/tCO₂ captured through BECCS.

Potentials for DACCS deployment have been obtained by adapting the values proposed in [15] and the estimates provided by [20], namely, a global level of 6.9 GtCO₂. The cost for DACCS (300-350 \$/tCO₂ captured) has been adapted from [15] (optimistic case) and [29] (in which a technology based on natural gas has been evaluated).

4 Scenarios with net-zero emissions

4.1 Oligopoly game outcome

The Nash equilibrium solution of the steady-state game, based on the nominal parameter values reported in Table 3, is summarized in Tables 4 and 5. The corresponding carbon price is 723 \$/tCO₂.

Table 4 indicates that CO₂ emissions are reduced from 46.8 Gt in BAU to 18.7 Gt in the steady-state regime (a 60% reduction). Emissions are compensated by removal activities that amount to 6.6 Gt for DACCS, 8.1 Gt for BECCS and 4.0 Gt for afforestation. Only India does not use its DACCS potential, due to the limited capacity of its reservoir for carbon sequestration, which is totally exploited by BECCS (the most cost-effective CDR activity). Note that the gross emissions associated of the Nash equilibrium solution are higher than the IPCC 1.5-2°C pathways [43] which range between 5.6 and

Table 3: Regional potential and cost of CDR measures

	Potential of CO ₂ capture [MtCO ₂ /yr]			Storage capacity [MtCO ₂]	Cost of CO ₂ capture [\$/tCO ₂]		
	AFF	BECCS	DACCS		AFF	BECCS	DACCS
USA	230	1,760	386	8,120	20	60	350
EUR	510	800	604	3,020	20	60	350
CHI	130	440	91	4,020	20	60	350
IND	140	991	310	1,000	20	60	300
RUS	170	600	2,036	12,340	20	60	300
GCC	80	219	1,248	3,928	20	60	300
QAT	10	24	137	982	20	60	300
OEE	80	40	370	4,460	20	60	300
ASI	1,730	1,068	740	5,560	20	60	300
LAT	600	600	652	9,030	20	60	300
ROW	300	1,657	370	26,620	20	60	300
World	3,980	8,199	6,944	79,080			

8.3 Gt of CO₂ in 2100. This can be explained by the difference in objective between the steady-state that looks for a net-zero emissions regime and the IPCC scenarios that continue in 2100 to eliminate emissions excesses with negative net emissions.

Table 4: Emissions, abatement and CDR [MtCO₂/yr]

	BAU emissions	Abatement	Emissions	AFF	BECCS	DACCS
USA	6,244	4,433	1,810	229	1,758	385
EUR	3,222	1,085	2,136	509	799	602
CHI	9,671	7,784	1,887	130	439	90
IND	3,990	2,807	1,183	139	909	0
RUS	1,529	785	744	169	599	2,032
GCC	1,533	1,050	483	80	218	1,245
QAT	183	100	82	10	24	136
OEE	6,517	3,296	3,221	80	40	369
ASI	5,757	2,670	3,087	1,728	1,066	739
LAT	1,195	622	573	599	599	650
ROW	6,985	3,495	3,490	299	1,655	369
World	46,824	28,128	18,696	3,972	8,106	6,618

(Emissions = BAU emissions - Abatement = AFF + BECCS + DACCS)

Worldwide, we observe a global welfare loss of -1.9% of GDP, w.r.t. the BAU situation. Main winners are Russia (+6% instead of -1.9%) and Latin America (+4.8% instead of -1.9%) while China, GCC countries and Rest of the World are negatively affected. The welfare cost for each region is given in Table 5.

Table 5: Welfare change and its components [% of GDP]

Welfare	Components						
	Abatement cost	Quota supply	GTT	AFF	BECCS	DACCS	
USA	-1.0%	-1.3%	0.6%	0.0%	0.0%	-0.2%	-0.2%
EUR	-1.1%	-0.7%	-0.3%	0.4%	0.0%	-0.1%	-0.4%
CHI	-3.8%	-2.4%	-1.8%	0.8%	0.0%	-0.1%	-0.1%
IND	-1.8%	-2.0%	-0.5%	1.8%	0.0%	-0.3%	0.0%
RUS	6.0%	-2.3%	17.4%	-1.4%	0.0%	-0.4%	-7.1%
GCC	-2.5%	-2.5%	9.4%	-4.1%	0.0%	-0.2%	-4.6%
QAT	-5.7%	-1.6%	5.4%	-4.5%	0.0%	-0.1%	-3.3%
OEE	-4.0%	-0.9%	-2.5%	-0.5%	0.0%	0.0%	-0.1%
ASI	-0.4%	-1.0%	0.4%	0.7%	0.0%	-0.1%	-0.3%
LAT	4.8%	-1.3%	8.5%	-0.1%	-0.1%	-0.3%	-1.8%
ROW	-3.3%	-1.3%	-1.5%	-0.2%	0.0%	-0.2%	-0.2%
World	-1.9%	-1.3%	0.0%	0.0%	0.0%	-0.1%	-0.5%

5 Sensitivity analysis

In this section, we perform a sensitivity analysis on CDR activity costs and on (long-term) demographic scenarios. These parameters are highly uncertain and potentially impacting both the evolution of CO₂ emissions and the mitigation responses.

5.1 CDR costs

We run the oligopoly model varying separately the costs of afforestation, BECCS and DACCS. Based on the literature review presented in Section 3.4, we consider the following assumptions:

- Afforestation cost: a range of 5-50 \$/tCO₂;
- BECCS cost: a range of 60-200 \$/tCO₂;
- DACCS cost: -50%, +50%, +100% and +150% w.r.t. the nominal value, resulting in a range of 150-875 \$/tCO₂.

Table 6 reports first the main results for all simulated scenarios on welfare impact, CO₂ price, abatement and amount of CO₂ captured. Figures 3, 4, and 5 detail next the impact on welfare change at a regional level of afforestation, BECCS, and DACCS costs, respectively.

Table 6: Global figures w.r.t. CDR cost

Cost variation	Welfare change [% of GDP]	CO ₂ price [2011 USD]	Abatement [MtCO ₂ /yr]	Captured CO ₂ [MtCO ₂ /yr]
AFF cost				
5	-1.9	723	28,122	3,973
20 (Nominal)	-1.9	723	28,122	3,973
30	-1.9	723	28,122	3,973
50	-1.9	723	28,122	3,973
BECCS cost				
60 (Nominal)	-1.9	723	28,122	8,107
100	-2.0	723	28,122	8,107
150	-2.1	723	28,123	8,106
200	-2.1	723	28,123	8,106
DACCS cost				
-50%	-1.7	723	28,120	6,624
Nominal	-1.9	723	28,122	6,622
+50%	-2.1	724	28,126	6,617
+100%	-2.4	744	28,385	6,358
+150%	-2.6	856	29,707	5,035

Table 6 indicates that only the variation of the DACCS cost has a significant global impact for the attainment of the net-zero emission regime. For instance, when assuming that the nominal DACCS cost is multiplied by two, the global welfare cost increases by 26% and reaches 2.4% of GDP. Marginally, a \$10 increase yields an average extra cost of 66 billion USD. Indeed, a higher DACCS cost reduces the amount of CO₂ captured, yielding more expensive abatement efforts. As displayed in Figure 5, the welfare cost of Russia, GCC and Qatar is highly dependent on the DACCS cost. When the latter is increased by 100%, Russian welfare change drops from 6% to -1% and the GCC one from -2.5% to -6.8%. However, CO₂ captured by DACCS remains quite unchanged, except when the cost of DACCS is 150% higher w.r.t the nominal value. In that case, CO₂ captured decreases by 23%. Regional welfare is also impacted by variations in the afforestation and BECCS costs, albeit at a reduced level. As displayed in Figure 3, LAT, ASI and Russia are the most affected regions by afforestation cost. Whereas Russia, India and the LAT region are the most negatively impacted by BECCS cost; see Figure 4.

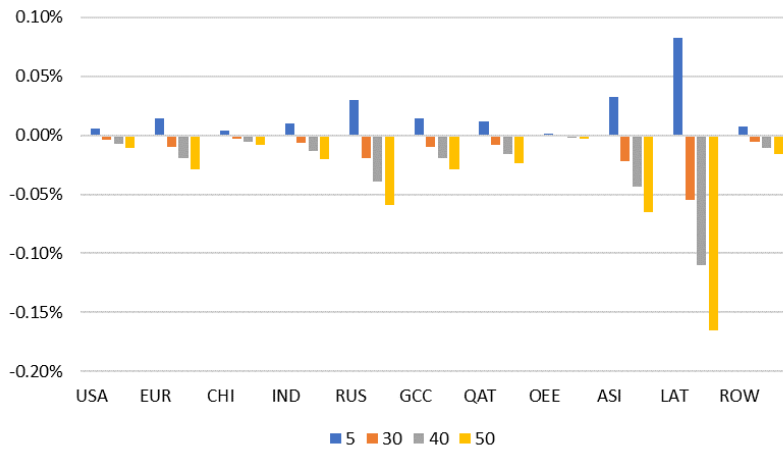


Figure 3: Regional change in welfare cost related to AFF cost [% of GDP w.r.t. the nominal scenario]

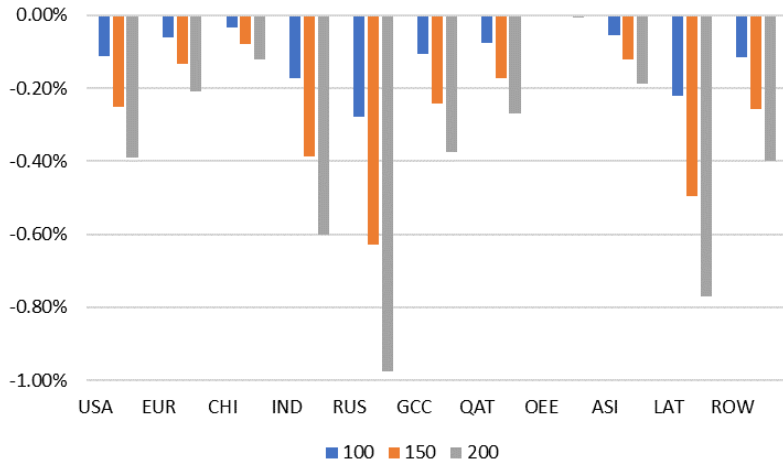


Figure 4: Regional change in welfare cost related to BECCS cost [% of GDP w.r.t. the nominal scenario]

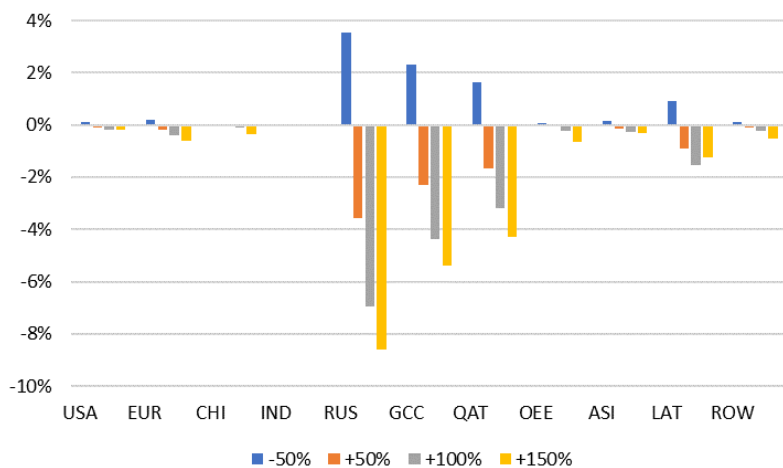


Figure 5: Regional change in welfare cost related to DACCS cost [% of GDP w.r.t. the nominal scenario]

5.2 Demographic scenarios

Table 7 shows the Nash equilibrium results for the oligopoly game under the three different demographic scenarios presented in Table 2. Results reveals the strong impact of demography on the steady-state regime. Indeed, more inhabitants leads to higher CO₂ emission levels in the reference scenario, which requires more efforts to attain a net-zero emission regime. More precisely, when we assume that population reaches 16.5 billions (high scenario), global cost increases by 88% to a level corresponding to 3.5% of GDP. Indeed, as the potentials of CO₂ captured by CDR activities are already completely used in the medium demographic scenario, additional abatements are required. The marginal abatement cost (carbon price) is multiplied by 2.2 and reaches \$1,574. Conversely, when population is limited to 7 billions (low scenario), world cost is reduced to 1.1% of GDP with an associated carbon price of \$350 as abatement is divided by two (level of 14.3 GtCO₂). Here, less than half of the DACCS potential is used, whereas levels of CO₂ captured by afforestation and BECCS are unchanged. In Table 8, we further detail CO₂ emissions, abatement and CDR activities at the regional level for the low scenario. These results confirm the decrease of abatement and DACCS activities w.r.t the medium scenario displayed in Table 4.

Table 7: Global figures w.r.t demographic scenario

	Low	Medium	High
Global welfare change [% of GDP]	-1.1%	-1.9%	-3.5%
CO ₂ price [USD 2011]	350	723	1,574
Abatement [MtCO ₂ /yr]	14,337	28,122	50,664
Emissions [MtCO ₂ /yr]	14,947	18,702	18,714
AFF [MtCO ₂ /yr]	3,970	3,973	3,975
BECCS [Mt CO ₂ /yr]	8,103	8,108	8,111
DACCS [MtCO ₂ /yr]	2,875	6,622	6,627

Table 8: Emissions, abatement and CDR [MtCO₂/yr] - Low demographic scenario

	BAU emissions	Abatement	Emissions	AFF	BECCS	DACCS
USA	4,078	2,528	1,550	229	1,757	0
EUR	2,020	381	1,640	509	798	224
CHI	5,357	3,815	1,542	129	439	89
IND	2,263	1,400	863	139	909	0
RUS	928	377	551	169	598	611
GCC	1,016	581	436	79	218	1,078
QAT	139	64	74	10	24	135
OEE	4,553	1,822	2,732	80	40	369
ASI	3,385	1,099	2,285	1,727	1,066	0
LAT	666	284	382	599	598	0
ROW	4,879	1,987	2,892	299	1,655	368
World	29,284	14,337	14,947	3,970	8,103	2,875

(Emissions = BAU emissions - Abatement = AFF + BECCS + DACCS)

In Table 9, we report finally on the regional welfare change in % of GDP w.r.t. the demographic scenarios. The discrepancy among the regions depends on their CDR potentials. Countries with high CDR potentials, e.g. Russia and GCC countries, increase their gains from CDR activities under the high demography scenario where there are more emissions to be sequestered. In comparison, welfare changes of USA, EUR and ASI regions are weakly impacted by demography.

5.3 Monte Carlo analysis

We present next a Monte Carlo analysis where one considers simultaneously several sources of uncertainty that could significantly affect the steady state outcomes. In addition to the previously studied parameters (CDR costs and demography), we consider as uncertain CDR potentials and three important economic parameters (abatement cost function, total productivity factor, and CO₂ emissions per capital factor). The probability distribution assumed for each uncertain parameter is given in

Table 9: Welfare change [% of GDP w.r.t demographic scenario]

	Low	Medium	High
USA	-0.5%	-1.0%	-1.7%
EUR	-0.4%	-1.1%	-2.7%
CHI	-1.9%	-3.8%	-6.3%
IND	0.1%	-1.8%	-4.6%
RUS	-1.1%	6.0%	11.8%
GCC	-4.9%	-2.5%	0.6%
QAT	-5.7%	-5.7%	-5.3%
OEE	-2.4%	-4.0%	-7.0%
ASI	0.2%	-0.4%	-1.8%
LAT	3.2%	4.8%	6.0%
ROW	-1.8%	-3.3%	-6.3%
World	-1.1%	-1.9%	-3.5%

Table 10. For CDR potentials, we assume a lower limit half our nominal value, and an upper limit twice our nominal value. The world afforestation potential is thus assumed to be in the range 2.0-8.0 GtCO₂/year, with an upper value below the one retained in [47] (namely, 13.8 GtCO₂). For the world BECCS potential, the assumed range is 4.1-16.4 GtCO₂/year, a rather conservative approach compared to the 2100 BECCS deployment values reported in the literature; see e.g. [36] for an intermodel comparison that provides a range of around 8-25 GtCO₂/year. Likewise, for the DACCS potential, we use a conservative approach compared to recent studies, see e.g. [39] that uses a range of 3-30 GtCO₂/year, whereas we assume a range of 3.5-13.9 GtCO₂/year. Despite the conservative approach chosen for selecting the CDR potentials, our values remain in the ranges provided by [35] in their literature review of CDR approaches. Concerning our uncertain economic parameters, the analysis performed in the previous section is based on a rather pessimistic view on the technical progress associated to CO₂ emissions (respectively parameters ν_j^2 and ν_j^3). Here, we assume a more optimistic view by considering probability distribution that are not centered on the deterministic case. Note finally, that parameter ν_j^1 associated to the total productivity factor is assumed to be in the range 0-2%.

Table 10: Uncertain parameters

Parameter	Probability distribution
AFF cost [USD]	Triangular(5, 20, 50) [†]
BECCS cost [USD]	Triangular(60, 60, 200)
DACCS cost [USD]	Triangular($0.5 \times \bar{x}$, \bar{x} , $2.5 \times \bar{x}$) [‡]
AFF potentials	Triangular($0.5 \times \bar{x}$, \bar{x} , $2 \times \bar{x}$) [‡]
BECCS potentials	Triangular($0.5 \times \bar{x}$, \bar{x} , $2 \times \bar{x}$) [‡]
DACCS potentials	Triangular($0.5 \times \bar{x}$, \bar{x} , $2 \times \bar{x}$) [‡]
Demographic scenario	Discrete: Low 0.25, Medium 0.5, High 0.25
Total productivity factor (ν_j^1)	Triangular(0, 1%, 2%)
CO ₂ emissions per capital factor (ν_j^2)	Triangular(-2.5%, -1%, 0)
Technical progress on the MAC function (ν_j^3)	Triangular(0, 0.3%, 0.9%)

[†] where the parameters a , b and c used in Triangular(a, b, c) refer respectively to the lower limit, the mode and the upper limit.

[‡] \bar{x} corresponds to the nominal regional value used in Table 3.

The Monte Carlo analysis involves an ensemble of 10,000 randomly generated scenario inputs. 97% of these parameter choices yield a Nash equilibrium computation. The 295 runs which fail to find a solution correspond to a situation where CDR potentials are too low. This is in line with the findings of [39] that highlights “*the key role negative emissions technologies can play in increasing the feasibility of ambitious climate targets*”.

Figure 6 presents first the distribution of carbon prices in \$/tCO₂. The modal price (441 \$/tCO₂) is much lower than the deterministic one (723\$/tCO₂). However, the distribution presents a big tail for high values up to 2,000 \$/tCO₂. This occurs for ‘extreme’ scenarios with a combination of high demography, CDR prices and abatement costs and low CDR potentials and productivity factors. On the other hand, in very favorable situations, the carbon price can be very low.

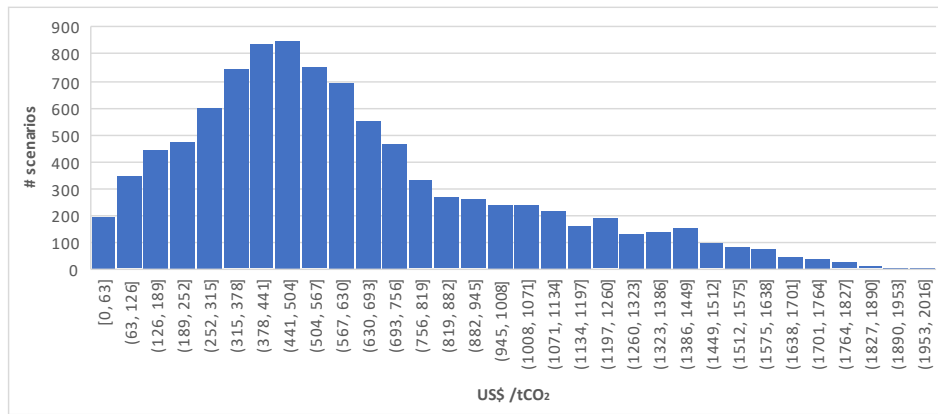


Figure 6: Probability distribution of carbon prices [USD]

The high variability of carbon prices induces significant disparities and variabilities for regional GDP losses, as displayed in Figure 7. Fossil fuel exporting countries (e.g., Russia and GCC) are among the most exposed when CDR strategies cannot be deployed at high scale and reasonable cost. In the worst case, Russia and GCC countries, and in particular Qatar, face a GDP loss of 60% and 50%, respectively. On the other extreme, in very favorable conditions, these countries obtain a 10-20% GDP increase. The advent of DACCS technologies based on natural gas could provide a better future for oil and gas exporting countries.

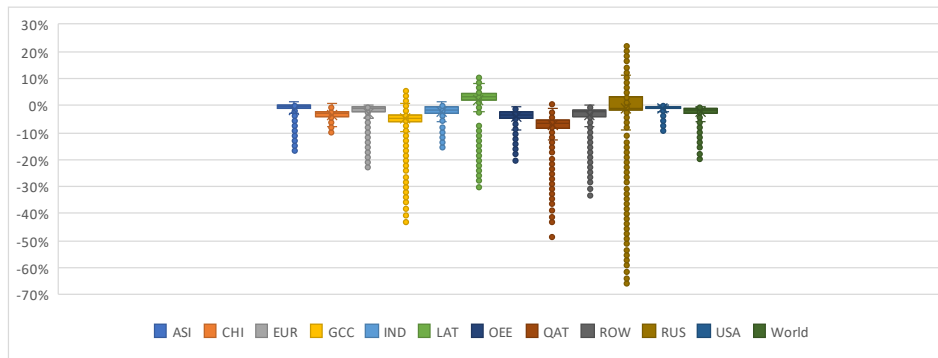


Figure 7: Regional welfare cost [in % of GDP]

The distribution of CDR activity levels is presented next in Figures 8 and 9. Total CDR activity ranges between 10 and 30 GtCO₂ with a modal value around 17-20 Gt of CO₂ close to the deterministic level.

6 Conclusion

It is challenging to predict the macroeconomic situation of the world at the end of the 21st century, when a zero-net emission regime is implemented to guarantee sustainability. Our approach is focused on the development of CDR activities in different regions of the world. This will generate negative emissions and thus permit a certain level of emissions in the economic sectors that remain dependent on fossil fuels. Negative emissions will thus become a commodity. An international carbon market is the most practical way to price this commodity. Any emitting industry will have to buy emission rights on the carbon market, which will be supplied by the CDR activities undertaken in different regions. Because different regions have different abatement costs, endowment in CO₂ sequestration capacities and CDR costs, the competition to supply negative emissions can be formulated as an oligopoly game, very similar to the ones that serve to represent oil, gas or natural resource markets today. The solution

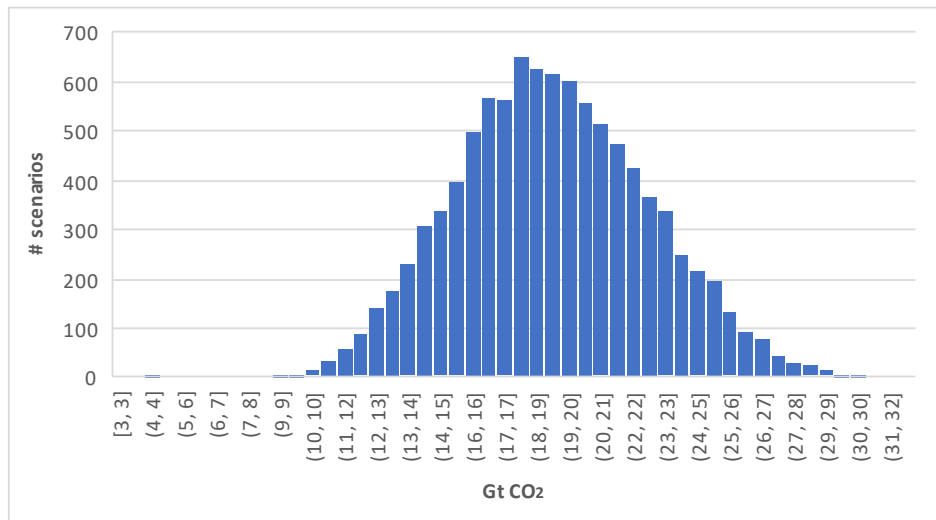


Figure 8: Probability distribution of total CDR activity [GtCO₂/yr]

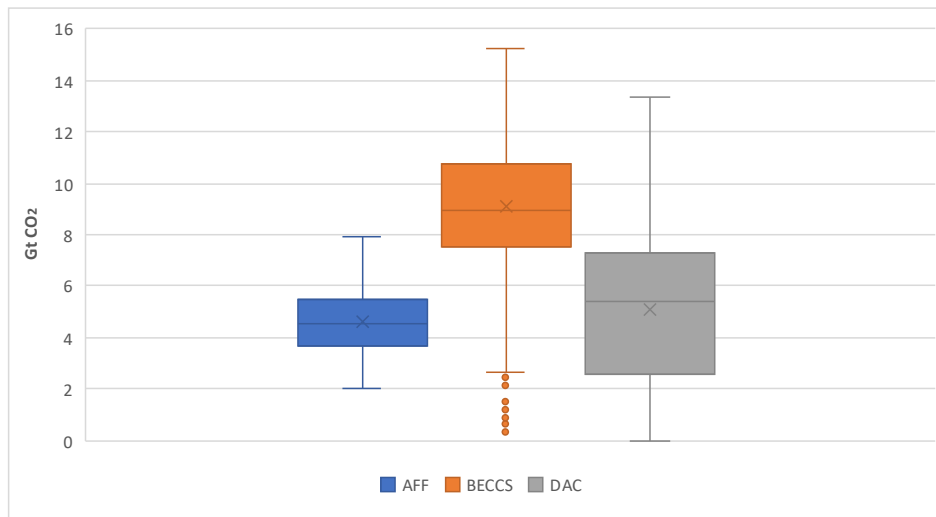


Figure 9: Detailed CDR activities [GtCO₂/yr]

of this steady-state model of net-zero emission regime could be used to define a target for end-of-period conditions in a dynamic integrated assessment model used to study the transition of the energy system from 2020 to 2100. Note that this steady state could remain valid on a longer term despite the limits on the reservoir storage capacities (e.g., in depleted oil and gas reservoirs, and aquifers) with the emergence of alternative storage options (e.g., deep ocean carbon sequestration).

The results from the simple sensitivity analysis show that demography is indeed among the main driver for a steady-state net-zero emission regime. Under a medium or high population assumption, almost all the potential of CDR is used and a high price of carbon is necessary to induce the needed abatements. Only in a low population-level scenario, the DACCS potential is not fully exploited. Indeed, when the DACCS cost is low, it provides a way to mitigate the abatement and changes in terms of trade costs for energy-exporting countries. Particularly true for Qatar, GCC or Russia, the latter gaining enormously in the medium and high demographic scenarios. It is interesting to note that the level of negative emission activities is lower in this steady-state model than for the end of the century in the dynamic transition model [4], which is using the same GEMINI-E3 simulations for calibration, but without end-of-period conditions. From the Monte Carlo exercise, we observe significant asymmetries in the computed carbon prices and welfare costs distributions. Although the modal price is much lower

than the deterministic one, the empirical probability distributions present a big tail for high carbon prices and welfare costs associated with extreme scenarios with high demography, CDR prices and abatement costs and low CDR potentials and productivity factors.

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