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Economic assessment of the development of CO_2 direct reduction technologies in long-term climate strategies of the Gulf countries

Frédéric Babonneau[1,3] · Ahmed Badran[2] · Maroua Benlahrech[2] · Alain Haurie[3,4] · Maxime Schenckery[5] · Marc Vielle[6]

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Abstract
This paper proposes an assessment of long-term climate strategies for oil- and gas-producing countries—in particular, the Gulf Cooperation Council (GCC) member states—as regards the Paris Agreement goal of limiting the increase of surface air temperature to 2°C by the end of the twenty-first century. The study evaluates the possible role of carbon dioxide removal (CDR) technologies under an international emissions trading market as a way to mitigate welfare losses. To model the strategic context, one assumes that a global cumulative emissions budget will have been allocated among different coalitions of countries—the GCC being one of them—and the existence of an international emissions trading market. A meta-game model is proposed in which deployment of CDR technologies as well as supply of emission rights are strategic variables and the payoffs are obtained from simulations of a general equilibrium model. The results of the simulations indicate that oil and gas producing countries and especially the GCC countries face a significant welfare loss risk, due to "unburnable oil" if a worldwide climate regime as recommended by the Paris Agreement is put in place. The development of CDR technologies, in particular direct air capture (DAC) alleviates somewhat this risk and offers these countries a new opportunity for exploiting their gas reserves and the carbon storage capacity offered by depleted oil and gas reservoirs.

Keywords GCC countries · Climate negotiations · Carbon dioxide removal · Financial compensation · Negative emissions · CDR technologies

1 Introduction

This paper provides an assessment of the possible mitigation of the macroeconomic cost for the Gulf Cooperation Council (GCC) countries incurred if the Paris Agreement goals are to be reached. In particular, we consider the possible contribution of carbon dioxide

✉ Frédéric Babonneau
frederic.babonneau@uai.cl

Extended author information available on the last page of the article.

removal (CDR) technologies in the definition of long-term strategies of the GCC countries to reach these goals. The CDR technologies considered include in particular biomass energy with CCS (BECCS)[1] and direct air capture (DAC)[2] with carbon sequestration. The GCC countries'[3] economies, largely based on oil and gas revenues, could be strongly affected in a worldwide drive toward a net-zero emissions regime, as implied by the Paris Agreement. This objective could be reached by 2070, or even as early as 2050, as discussed in COPs 22-24. The contribution of this paper is mainly methodological and prospective. We do not discuss the negotiations leading to a new international agreement; rather, we propose an original macroeconomic framework for assessing the role that CDR technologies could play in reaching a worldwide transition to net-zero emissions and their possible impacts on oil and gas exporting economies.

The current stance of the GCC countries is to resist the international drive toward more rapid global abatement because it exposes them to a very high risk for stranded assets. Indeed, a recent IPCC report (Rogelj et al. 2018) presents several emission trajectories proposed by different integrated assessment models for abiding by Paris Agreement objectives. All these trajectories impose a very stringent abatement trajectory reaching net-zero emissions before the end of the century. Of particular interest to oil- and gas-producing countries, the Sky scenario—developed by Shell Corporation (Shell-Corp 2018)—indicates also that the Paris Agreement implies reaching net-zero emissions in 2050 (or 2070, at the latest), followed by a period where net-negative emissions occur with declining atmospheric CO_2 concentration. To reach this net-zero and then net-negative emissions, the Sky scenario proposes a profound transformation of energy systems. By 2070, solar will account for 32% of primary energy sources, and wind for 13%. Oil, natural gas, and coal will account for 22% and will be associated with carbon capture and storage (CCS). Additionally, and also associated with CCS, bioenergy will account for 14%.

BECCS, which consists in a biomass-based combustion power plant with CO_2 capture, is the technology of choice for negative emissions in the Sky scenario. In this process, biomass absorbs CO_2 while growing, and then the power plant captures the CO_2, therefore resulting in negative emissions. A drawback of choosing BECCS as the main negative emission technology is the logistics of production and transportation of biomass fuels, which will compete with food production and afforestation/reforestation (Winchester and Reilly 2015). Another option—much costlier, but likely of strategic importance to oil and gas producing countries, and especially the GCC if a high carbon price is set worldwide—comes in the form of DAC. Developing DAC technologies as a standard industrial process, however, requires investment and is constrained by access to clean energy sources and CO_2 storage capacities.

Among several recently proposed scenarios for global, long-term strategies that comply with the Paris Agreement, the DAC appears as a promising technology for attaining a net-zero emissions regime (Meadowcroft 2013). For example, Marcucci et al. (2017), uses the MERGE-ETL model (Kypreos and Bahn 2003; Kypreos 2007) to show that a DAC technology can play an important role in realizing deep decarbonization goals and in reducing regional and global mitigation costs. Indeed, under the 2°C and 1.5°C scenarios analyzed, a DAC technology will capture 21 and 40 $GtCO_2$, yearly by 2100, respectively; will attain a net-zero emissions regime by 2075 and 2040, respectively; and will be responsible for very large negative emissions at the end of the planning horizon. In these scenarios, the gas- and

[1]For a recent presentation and discussion of BECCS potential, see Baik et al. (2018) and Consoli (2019).
[2]For a recent presentation and discussion of DAC, see Keith et al. (2018).
[3]Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

oil-producing countries of the Middle East are expected to have a competitive advantage in developing DAC because of their access to large carbon sequestration storage capacities. In this regard, a recently published paper (Keith et al. 2018) gives a complete feasibility and techno-economic assessment of a DAC technology that uses natural gas for providing needed power and heat. As described, this represents another comparative advantage for the development of DAC technologies in gas-producing regions: by transforming their natural gas endowment and sequestration capacity in depleted oil and gas reservoirs into negative emissions, the GCC countries and other oil- and gas-exporting countries could, if the price of carbon incentivizes it, have access to a new, high economic value resource—emission rights.

Inspired by the insights provided in Meadowcroft (2013) and Marcucci et al. (2017), this paper focuses on GCC countries by building upon the results of a more encompassing macroeconomic model. We use a dynamic game formulation of the strategic competition among different groups of countries in reaching the Paris Agreement objectives. Briefly, to assess the future price of carbon, we use a general equilibrium model, which evaluates the macroeconomic costs of long-term climate strategies for 10 groups of countries (the GCC being one of them). These groups of countries are defined as "natural" coalitions in climate negotiations that will almost certainly take place in implementing the Paris Agreement. To represent possible competition among these groups of countries, we use a non-cooperative game model that describes the strategic supply of emissions rights in an international carbon market. Strategies for each group of countries include abatement decisions and developments in CDR technologies.

The model assumes a transition toward a net-zero emissions climate regime with a limited cumulative emissions budget over the 2020–2100 period, compatible with 2°C warming by 2100. International cooperation is represented by sharing agreements for the remaining cumulative emissions budget[4], where the supposed financial transfer mechanism to be implemented in the Paris Agreement is represented by trading permits in an international emission rights market. With the associated abatement path and development of CDR activities, optimal exploitation of coalitions' shares of emissions budgets is given by a Nash equilibrium in a dynamic game model. This meta-modeling approach—where a dynamic open-loop game is calibrated using statistical emulation of a large sample of simulations, performed with a world general equilibrium model—was first proposed in Haurie et al. (2014) and has subsequently been used in several analyses of climate policies (Babonneau et al. 2016, 2018). The new contribution of this work lies in the explicit consideration of the GCC economies and the introduction of CDR activities as a strategic choice for coalitions.

Under this framework, we provide an assessment of the contribution of CDR technologies in lowering global mitigation costs, and demonstrate some comparative advantages to oil and gas exporting countries in future long-term climate regimes. Additionally, although a GCC coalition may currently seem unlikely, we show in this study that the GCC countries share common economic risks and opportunities, justifying a much broader cooperation over the next few decades. The results obtained in this study complement previous works (Stephan and Paterson 2012; Marcucci et al. 2017; Peterson and Weitzel 2016) in several ways: (i) they provide an assessment of GDP and welfare losses based on a general equilibrium model; (ii) they estimate the impact of CDR technology on an International Environmental Agreement, represented by a shared safety cumulative emissions budget;

[4]A safety cumulative emissions budget of 1 trillion ton carbon has been shown to be compatible with the 2°C goal (Rogelj et al. 2018).

(iii) and they propose a possible solution that would limit welfare loss to 2.8% of discounted cumulative GDP for every coalition.

The paper is organized as follows. In Section 2, we present challenges facing the GCC countries in attempting to define a long-term climate strategy. In Section 3, we develop the macroeconomic framework that we use for our assessment. In Section 4, as part of a global worldwide effort to reach a net-zero emissions regime, we present the simulation results obtained under this modeling framework and focus particularly on GCC countries and the potential impact of developing DAC technologies. Finally, in Section 5, we discuss policy implications and conclude.

2 Challenges for the GCC countries

The long-term goal established by the UNFCCC in Paris—and reaffirmed in the subsequent COPs—implies reaching a global net-zero emissions regime before the end of the century. This is indicated in the latest IPCC reports, as well as in several integrated assessment models (e.g., Paltsev et al. 2018). In this context, climate negotiations seek to drastically reduce fossil fuel consumption, which would thus seriously impact energy exporting countries' economies (McGlade and Etkin 2014). Notably, the GCC countries are part of the Paris Agreement, operating within the Arab Group[5] as their primary negotiating bloc. Here, although Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE) are all members of the Cooperation Council for the Arab States of the Gulf, there are some fundamental differences among those countries which have resulted in diverse policies and strategies. For example, financial resilience differs widely: while Kuwait and Saudi Arabia possess large financial reserves and debt capabilities, Qatar, UAI, and Oman show less financial strength to support shocks on oil demand and prices (International Energy Agency 2020). As such, it is not currently possible to consider the GCC a unified entity, nor ignore these differences among its member states.[6]

Indeed, such differences could impact their respective positions toward climate change issues or their ability to act as a unified block and defend their common interests in global negotiations. Nevertheless, all signatory countries must find a way to cooperate on the global challenge posed by the climate change issue and in reaching a net-zero emission regime by the end of the century; and indeed, do so while negotiating to obtain, over the long-term, fair terms of burden sharing. To be sure, the GCC countries share similar exposure to climate change damages, similar exposure to stranded asset risks, and similar access to CO_2 sequestration in depleted oil reservoirs. For these reasons, notwithstanding the differences discussed, our modeling approach considers that the GCC countries form a natural coalition to balance the relative negotiating power of different groups of countries around the world.

Several approaches have attempted to define a "road map" for reaching the goals of the agreement, e.g., in the IEA Sustainable Development scenario (International Energy Agency

[5]The Arab States is comprised of 22 member states namely Algeria, Bahrain, Comoros, Djibouti, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Mauritania, Oman, Palestine, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, United Arab Emirates, Yemen.

[6]As is the case between many member states of other regional organizations, the GCC member states hold different positions in relation to different regional and international issues. There is a lack of consensus for example with regard to determining common interests and defining security threats. There are also some major differences among the GCC countries regarding their foreign policies and their positions concerning the Arab spring.

2020) or the Shell Sky scenario (Shell-Corp 2018). Discussions of the most efficient means to coordinate international efforts have explored uniform carbon taxes and an international carbon market based on a cap and trade mechanisms (see Gollier and Tirole 2015). The basic premise of this paper is thus based on the assumption that there will be negotiations leading to an international emissions trading scheme with a burden-sharing approach to emissions reductions. Even though such a development may appear highly unlikely, the situation described in this study serves as a benchmark, and is certainly more efficient than the one which will emerge from the COP negotiations. This hypothetical assumption of an efficient world is required for drawing economic assessment conclusions concerning long-term strategies for the GCC countries, and assuming a trading scheme is useful for comparing different political solutions toward implementing COP agreements and in quantifying possible economic outcomes.

3 A global macroeconomic framework

Expanding upon previous studies dealing with the assessment of economic impacts of the Paris Agreement (Babonneau et al. 2016, 2018), we introduce a macroeconomic framework that combines a computable general equilibrium (CGE) model, namely GEMINI-E3, with a dynamic game model. The resulting "meta-game" model—under simplifying, but reasonable assumptions—is used to provide a first insight into possible welfare losses in GCC countries, if they were to implement a long-term mitigation strategy with CDR technologies. The full mathematical description of this model is given in the Electronic Supplemental Material.

Briefly, the model describes 10 coalitions of countries (including a grouping of GCC countries) competing for the supply of emissions permits in an international cap and trade system as designed to satisfy a global safety cumulative emissions budget (evaluated at 1170 GT of CO_2 over the 2020–2100 period). A net-zero emission regime is reached at the end of this period. To summarize climate negotiations on the burden sharing issue, we consider different possible allocations of a global safety cumulative emissions budget among different coalitions. Once the share of the emissions budget that goes to each coalition is decided, the coalitions are assumed to play a non-cooperative game for the supply of emissions permits in the international carbon market. Depending on their respective abatement policies, the coalitions can be net buyers or net sellers of permits. This generates payment transfers that converge toward fair burden sharing. Furthermore, our modeling approach encapsulates several key elements of the design of an international climate regime consistent with Paris Agreement goals. The payoffs for the game-theoretic model are obtained from statistical emulation of the GEMINI-E3 CGE model presented below.

3.1 Evaluation of welfare losses with the GEMINI-E3 model

GEMINI-E3 (Bernard and Vielle 2008) is a CGE model specifically designed to assess the impact of climate change mitigation policies in different regions of the world. It has recently been used to assess the COP21 pledges and a fair 2°C pathway compatible with the Paris Agreement objectives (Babonneau et al. 2018). For this study, the model has been extended to permit a more detailed representation of the GCC countries and their risk exposure to stranded assets. The model is built on the GTAP 9 database (Aguiar et al. 2016), with reference year 2011. In this version, we detail 10 groupings (regions or coalitions) of countries, the GCC countries being one of them; they are as follows: European Union (28 countries), USA, China, India, the GCC, Russia, other Asian countries, other energy-exporting

countries, Latin America, and the rest of the world.[7] Extraction of fossil fuel energy is modeled by carbon content in order to evaluate the "unburnable-oil" effect of climate change mitigation policies. Three fossil fuel sectors/products are represented: coal, crude oil, and natural gas. In the model, the impact of deep decarbonization pathways on stranded fossil fuel assets occurs via two main channels: (i) fossil fuel resources localized in energy exporting countries lose their value, energy rents associated with these resource decrease (i.e., inground reserves become stranded assets), and welfare is directly negatively impacted in countries that own these resources; (ii) capital invested in energy sectors (coal mining, refineries, pipeline infrastructure) and energy-intensive industrial sectors are further depreciated, which in turn negatively impacts households that own these assets. In GEMINI-E3, like most CGE models, households own capital and other resources, e.g., land, fossil fuel resources. While we do not consider national oil companies, nevertheless where NOCs are owned by the government, our results are not affected. Indeed, our scenarios assume that the government budget is unchanged with respect to the reference scenario. In this sense, a decline in oil revenue allocated to the government budget requires an increase in household taxation (e.g., direct tax) and a decrease in household income equivalent to our current closure rule.

Since GEMINI-E3 was designed to run on the 2011–2050 period, we take a versatile approach to extend it to 2100 based on steady-state growth through the end of the century. We first, selected a demographic scenario, then used a production function approach to indicate the relationship between GDP per capita and the total factor productivity (TFP). We assume that regional TFPs converge to an exogenously defined common value at the end of our century, represented by the US figure. Finally, we also assume that CO_2 emissions per unit of GDP decrease at an annual rate and converge also to a single common value for each region. This allows us to simulate a BaU scenario through 2100 by setting a value for the three parameters defined above: demographic scenario, TFP, and a carbon intensity per GDP. In this paper, we assume that the TFP and carbon intensity per GDP converge to 1% and -1%, respectively at the end of our century.[8]

This macroeconomic model reproduces historical emissions (2011 to 2018) and its medium term forecast is based on the WEO outlook 2016 (International Energy Agency 2016). The economic impact of mitigation policies is measured by the gains (or losses) in terms of trade (GTT) and the domestic abatement costs.[9] For energy-exporting countries, like the GCC countries, the GTT component represents decreases in energy exporting revenues. CDR technologies are not modelled in GEMINI-E3 since they are new technologies

[7]The GTAP database is a well-established economic database, used by the majority of CGE models and international economic institutions (OECD, European Commission, IFPRI, etc). The GTAP consortium and the collaborators have continuously improved the quality of the database. Although, some developing countries lack accurate input-output tables—and so their data are probably less reliable—this is not the case for GCC countries. Data on these countries have undergone extensive improvements over recent years. The authors would like to specifically mention the efforts of David Green, who has built the input-output tables embedded in GTPA8 for Saudi Arabia, Qatar, Kuwait, Oman, Bahrain, and the UAE. More recently, input-output tables for Saudi Arabia have been reported in the OECD Input-Output Tables 2018 Edition.

[8]The convergence of TFP is well documented. See, for example, Fouré et al. (2012), which used empirical analysis to derive convergence of 147 countries toward a 1% TFP growth rate (corresponding to the US figure). While convergence of carbon intensity is less discussed in the literature, energy projection analyses (e.g., World Energy Outlook (International Energy Agency 2020)) are suggestive of such behavior in scenarios without stringent climate policy. It is thus a reasonable assumption to set carbon intensity to a 1% growth rate at the end of the century.

[9]Determined from deadweight loss of taxation (DWL) (Bernard and Vielle 2003).

with strategic importance in their development for oil- and gas-exporting countries. In addressing this, our game model includes explicit decision variables for the investment and use of these technologies.

3.2 Meta-Game model and linkage with GEMINI-E3

First proposed in Haurie et al. (2014), the meta-game model presents coalition payoffs as a function of the macroeconomic costs of abatement policies, the cost of developing CDR technologies, the gains in the terms of trade (GTT) due to global impacts on world energy prices, and the financial gains or losses from trading permits. Statistical emulation of the macroeconomic model are used to calibrate marginal abatement costs and GTT functions.

Regression analysis is used to estimate the payoff functions of the game, where strategic variables are the quotas supplied by the different coalitions, at different times, under an emissions trading scheme. Statistical analysis is based on a sample of 100 numerical simulations of different possible climate policy scenarios performed with GEMINI-E3, as detailed in the Electronic Supplemental Material.

3.3 Introduction of CDR alternatives

3.3.1 Brief review of CDR technologies

CDR aims to remove carbon dioxide directly from the atmosphere through different processes that either increase natural carbon sinks—such as oceans and lands—or use chemical engineering to suppress carbon dioxide. Of potential geo-engineering approach (Heyward 2013), CDR technologies are considered less environmentally impactful than stratospheric aerosol injection (SAI), marine cloud brightening, or space reflectors. Within CDR, several approaches have already been tested and implemented, including ocean iron fertilization[10], biochar[11], enhanced weathering[12], large-scale afforestation[13], BECCS, and DAC. Our analysis focuses on only the last two technologies, which are the most likely backstop technology candidates (Shell-Corp 2018; Chen and Tavoni 2013).

3.3.2 Techno-economic analysis of CDR technologies

Assessments of DAC technologies are discussed in Keith et al. (2006) and Keith (2009), and more recently, in House et al. (2011) and Keith et al. (2018). Their potential role in climate stabilization has been explored in Nemet and Brandt (2012), and then in Chen and Tavoni (2013), under the WITCH model (Bosetti et al. 2006), which predicts comparative advantages in deploying DAC for the Middle East and energy-exporting countries. This same comparative advantage was also observed in Marcucci et al. (2017), which used

[10]Ocean fertilization refers to the intentional addition of iron into the ocean to stimulate phytoplankton growth.

[11]Biochar refers to a "green coal" obtained by pyrolysis of biomass, such as crop or forestry residues, for the latter use in agriculture enhancement, leading to carbon sequestration.

[12]Enhanced weathering uses the physicochemical properties of certain rocks capable of extracting carbon dioxide (CO_2) from the atmosphere that fixes it in solid form.

[13]Generally classified in the category of land-use management (Nabuurs et al. 2007).

the MERGE-ETL model (Kypreos 2007) to explore the potential of the DAC technology. Under these models, the total quantity of CO_2 captured by the DAC and other carbon capture technologies is constrained by the potential for CO_2 storage across regions. As derived in Marcucci et al. (2017), estimates of storage potentials—including deep saline aquifers, hydrocarbon fields, and coal beds—are given in Table 1. Due to potential technical, accessibility, and social acceptance issues—among others—we assume that only a fraction (between 25 and 50%) of these potentials can be used for the DAC and BECCS operations by 2100. We also assume that the DAC technologies will be mature enough for massive deployment by 2040 with a linear deployment trend afterwards.

Cost of DAC has been discussed in recent publications. For instance, Keith et al. (2018), describes and economically assesses a process fully powered by natural gas, computing a levelized cost of 232 \$/t-CO_2 captured; an American Physical Society study (The American Physical Society 2011) proposed a levelized cost of 550 \$/t-CO_2; House et al. (2011) determined the cost for powering a DAC plant using a natural gas-fired plant with CCS at 396 \$/t-CO_2 avoided; and the extra energy cost of DAC was estimated around 232 \$/t-CO_2 captured by Lackner (2009) and Gardarsdottir et al. (2014) and Gardarsdottir et al. (2018). Storage costs were evaluated in Rubin et al. (2015) to be in the range of 6 to 13 \$/t-CO_2 stored. The total levelized cost is thus here set at \$300/t-CO_2 captured and stored, for all regions except the USA and EUR. These latter costs are priced at \$350/t-CO_2 captured and stored, assuming higher logistic costs.

As for BECCS, the technology standard consists of producing electricity from biomass while capturing and injecting CO_2 into geological formations. We use a unique levelized cost of 60\$/t-CO_2 for the whole world, consistent with the IEA estimates (Koornneef et al. 2011). BECCS potentials are estimated from the global and regional assessments (Koornneef et al. 2011), which take biomass supply chains and processing into account, and also include deployment issues in terms of policy and regulatory barriers. Using the IEA estimates, we have derived a global bound on GHG captured through BECCS equal to 10.2 Gt CO_2, based on technical potentials by 2050. Finally, BECCS penetration is related to electricity generation levels and composition by year 2050; we adopt what could be considered rather conservative potential estimates for the end of the century.

Table 1 Carbon storage potential in $GtCO_2$

		Storage potential
EUR	European Union (28 countries)	24.0
USA	United States of America	37.5
CHI	China	30.5
IND	India	20.0
GCC	Gulf Cooperation Council	126.5
RUS	Russia	86.0
ASI	Rest of Asian countries	23.0
OEE	Other energy exporting countries	46.0
LAT	Latin America	40.5
ROW	Rest of the World	23.0
	World	447.0

3.4 Evaluation of fair compensations among GCC countries

To assess the economic consequences of a proposed climate agreement, we assume "optimal" use—or at least, a second best solution—of the global emissions budget, which will correspond to a Nash equilibrium among the parties. In this sense, we assume a global safety cumulative emissions budget (SCEB) of 1170 Gt of CO_2 over the time horizon 2018–2100. Climate negotiations, in one form or another, will bear how this global safety cumulative emission budget is shared among coalitions, regrouping countries with similar macroeconomic structure. We also assume an international emissions trading system. Here, the coalitions supply permits to the market, strategically crafting abatement policies for their share of the safety cumulative emissions budget. In this sense, the development of CDR activities like BECCS and DAC will allow coalitions to replenish or increase their own emission budget. We compute a Nash equilibrium around this dynamic game. Briefly, when a coalition reaches capability for a levelized cost of a CDR technology—be it BECCS or DAC—lower than the price of permit, it can then invest to increase the permit allowances and gain advantages in the equilibrium solution. We consider a fair burden sharing is obtained when the share of the remaining safety cumulative emissions budget that is given to each coalition is such that the relative losses of welfare are equal among all coalitions. For the GCC countries, the financial transfers from selling permits through the market will generate compensations for unburnable oil.

4 Simulation results

4.1 The reference scenario

Using GEMINI-E3, we build a BaU scenario—calibrated on the "New Policies" scenario from the World Energy Outlook 2016 (International Energy Agency 2016)—for the period 2017–2050. We extend this BaU scenario to the 2050–2100 period, following (Babonneau et al. 2020). Demographic assumptions are based on the United Nations "median variant" scenario (United Nations 2017). World population increases by 50% from 2016 to 2100, and reaches 11.2 billion inhabitants in 2100. During the same period, the BaU scenario assumes that global GDP multiplies sevenfold—representing a 2.4% annual growth rate—and that global CO_2 emissions reach a maximum of 48.3 billion tons of CO_2 in 2050, and then decrease down to 46.8 billion tons of CO_2 at the end of the century. This decline in emissions is expected from rarefaction of fossil energies over the second half of the twenty-first century. According to this scenario, more than 4.11 trillion tons of CO_2 are emitted during the twenty-first century. Such an emissions budget would lead to an increase of surface air temperature over 3.5°C with regard to 1850–1900 period, with probability 66% (see Rogelj et al. 2018).

4.2 Impact of CDR activity in global mitigation scenarios

In contrast to the BaU scenario, we consider an SCEB of 1170 Gt of CO_2 for 2018–2100, under two scenarios with and without CDR technologies. This budget is consistent with the recent IPCC report (Rogelj et al. 2018) on the pathway to 2°C. We also assume that very stringent climate policies can be implemented only after 2030.

Figure 1 shows the global trajectory of CO_2 net emissions with and without DAC/BECCS. Net emissions are equal to CO_2 emissions minus DAC/BECCS sequestered

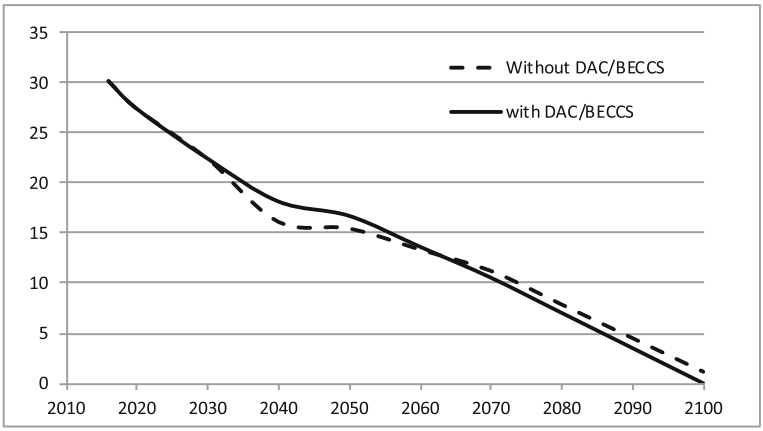


Fig. 1 Net emissions in Gt CO_2 with and without DAC/BECCS

emissions. The dual variable of the SCEB constraint is used to define a CO_2 price. Table 2 gives the CO_2 price and the worldwide welfare lost.

Without CDR, more abatement is required (see Fig. 2), and this implies a more restrictive timeline where CO_2 emissions converge to zero at the end of the twenty-first century. Moreover, this results in a significant welfare loss, 3.8% of the discounted GDP over the 2018–2100 period. When DAC and BECSS are used, however, the worldwide welfare loss is reduced to 2.8%. Without CDR technologies, the CO_2 price given by the dual variable of the budget constraint is equal to 4140$ in 2100 which corresponds to 775$ in 2030[14]. This shows the extreme stringency of the climate target when the CDR technologies are not available. With CDR technologies, the CO_2 price is 1292$ in 2100 corresponding to 480$ in 2030[15]. These figures are consistent with those in the IPCC special report on Global Warming of 1.5°C (Rogelj et al. 2018). Indeed, under the Higher-2°C pathway, the range estimates in the IPCC report are equal to 15–200$ in 2030 and 175–2340$ in 2100. This shows that CDR technologies allow for reaching the net-zero emission target, and that DAC activity additionally becomes highly profitable at the end of the century. Figure 2 represents the same two mitigation scenarios showing the contribution of DAC and BECSS.

Figure 3 shows variation in global welfare loss under the scenarios with the target SCEB and CDR options. The 2°C threshold corresponds to the 1170 SCEB discussed above. The diagram shows that the 1.5°C objective appears to be very challenging (Rogelj et al. 2015; Mitchell et al. 2016), with a cost multiplied by 5. This is also suggestive that the 1.5°C scenario is highly unlikely due to its cost.

To complement this analysis, we have also simulated a scenario of full cooperation among all nations. The model assumes implementation of policy which minimizes the total cost for the whole world, without any constraints on the timing of abatements is implemented. While the "utopia" scenario decreases global percentage loss of GDP, over the second-best solution, from 2.8 to 2.1%, the two values are not entirely dissimilar.

[14]This corresponds to a CO_2 price of 1043$ in 2050 and 1873$ in 2070.
[15]This corresponds to a CO_2 price of 645$ in 2050 and 1165$ in 2070.

Table 2 CO_2 price and welfare cost in the period 2018–2100 assuming a safety budget of 1170 Gt CO_2 and a 3% discount factor

DAC & BECCS	Without	With
Discounted CO_2 price (ref. 2030) in $\$_{2010}$	775	480
Discounted World cost in % of discounted GDP	3.8%	2.8%

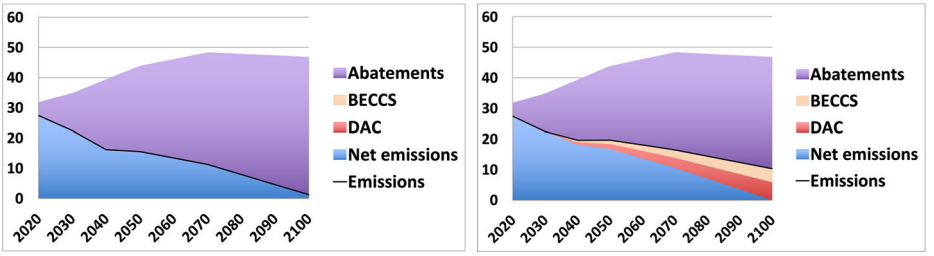


Fig. 2 Net emissions, DAC, BECCS, and abatement profiles without (left) and with (right) DAC/BECCS (in Gt CO_2)

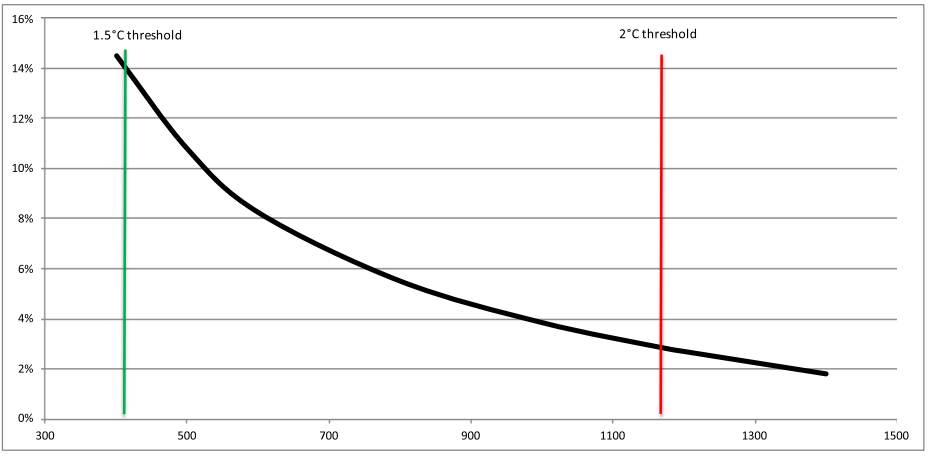


Fig. 3 Discounted global welfare cost in % of discounted GDP with respect to carbon budget in Gt CO_2

Table 3 Budget shares and welfare losses for two allocation rules

	Grandfathering allocation in %	Welfare cost[a]	Per capita allocation in %	Welfare cost[a]
USA	16.6%	1.3%	4.0%	4.0%
EUR	11.2%	1.4%	4.3%	2.8%
CHI	27.2%	1.2%	15.1%	4.0%
IND	6.3%	3.0%	17.2%	−4.5%
RUS	4.5%	6.9%	1.5%	11.4%
GCC	2.9%	11.0%	0.9%	13.8%
OEE	8.8%	4.7%	11.6%	3.9%
ASI	11.8%	2.4%	17.5%	1.4%
LAT	3.0%	2.9%	4.5%	1.1%
ROW	7.7%	6.4%	23.3%	−0.1%
World	100.0%	2.8%	100.0%	2.8%

[a]Discounted welfare cost in % of discounted GDP

4.3 Fair allocation of SCEB across GCC countries

Prior to designing possible fair sharing agreements, we first explore the economic impacts that would occur under the implementation of two quota allocations, extensively discussed and analyzed in the literature: "Grandfathering" and "Per Capita." Table 3 shows the budget shares and welfare losses under these two rules. In neither cases is fairness achieved, and the GCC countries are moreover disadvantaged at 11% and 13.8% of discounted GDP losses, respectively. Indeed, the relatively few permits allocated to the GCC countries—2.9% under Grandfathering, and 0.9%, under Population—appear to be largely insufficient to compensate for their revenue losses in world energy markets.

Table 3 shows the effects from these rules. Grandfathering allocates quotas proportional to emissions in the BaU scenario over the whole period (2018–2100). This idea is meant to take existing situations into account as a starting point in environmental negotiations, on the basis of the principle of sovereignty. Under this allocation, energy-exporting countries (Russia, the GCC countries, and OEE) and the Rest of the World[16] incur a very high burden, while India, Latin America, and China largely benefit. The second rule, per capita, sets the budget share proportional to the population over the 2018–2100 period. This equalitarian rule creates a large number of extreme welfare impacts. The most populated countries earn significant revenues by selling emissions. Therefore, India, the Rest of the World, and Latin America experience improvements in welfare by implementing climate mitigation policy, while energy exporting countries—as well as China and the USA—bear significant welfare loss. The difference between China and India, which have comparable populations, is because the former has a much higher per capita CO_2 emission rate stemming from higher economic development and greater dependence on coal.

To address the issue of fair distribution of the SCEB, we follow the approach proposed in Haurie et al. (2014). We propose a burden-sharing rule that equalizes welfare losses among the 10 groups of countries. This so-called "Rawlsian" allocation seeks to maximize welfare

[16]Rest of the World regroups many developing countries.

Table 4 Burden-sharing and welfare cost with Rawlsian rule in percentage difference from the reference scenario

	Budget share	Welfare cost[a]	Components of welfare cost[a]				
			Abatement	DAC	BECCS	GTT	Emissions trading[b]
USA	9.07%	2.84%	1.78%	0.17%	0.32%	−0.02%	0.58%
EUR	4.31%	2.84%	0.82%	0.33%	0.24%	−0.41%	1.87%
CHI	19.93%	2.84%	3.72%	0.20%	0.15%	−0.63%	−0.61%
IND	6.53%	2.84%	3.49%	0.29%	0.57%	−1.33%	−0.18%
RUS	7.01%	2.84%	3.16%	6.22%	1.29%	1.89%	−9.70%
GCC	8.81%	2.84%	3.30%	5.38%	0.02%	5.55%	−11.39%
OEE	15.57%	2.84%	1.68%	0.19%	0.14%	0.99%	−0.16%
ASI	9.45%	2.84%	1.45%	0.28%	0.23%	−0.69%	1.56%
LAT	3.00%	2.84%	1.83%	1.56%	1.22%	0.11%	−1.88%
ROW	16.31%	2.84%	2.53%	0.27%	0.19%	0.32%	−0.47%
World	100.00%	2.84%	2.04%	0.54%	0.29%	0.00%	0.00%

[a]Discounted welfare cost in % of discounted GDPDiscounted welfare cost in % discounted GDP

[b]Negative (positive) values are for net sellers (buyers)

for the worst affected countries. Table 4 displays the resulting fair allocation of quotas, a breakdown of costs among abatement and DAC and BECCS activities, and GTT and permit exchanges on the international emission market. Here, the GCC countries and Russia are enabled to sell emission rights to offset losses in fossil energy-exporting revenues and DAC activity cost. On the other hand, industrialized countries (e.g., USA, Europe, and Japan) are the main buyers of permits, and transfer financial compensations to the GCC countries. In short, once there is agreement on the principle of an international carbon market and of distributing a global safety cumulative emissions budget, the market will generate compensations.

We compare these results via a sensitivity analysis to evaluate the impact of DAC costs and potentials on the burden sharing agreement. We define a set of scenarios that place DAC sequestration potentials from 12.5 to 50% and costs from 200 to 1000 US$ per ton of CO_2 sequestered. Figures 4 and 5 show global welfare loss in % of discounted GDP and the fair GCC budget shares, respectively

We observe in Fig. 4 that welfare loss of the total discounted GDP varies reasonably, 2.7% under the "low price-high potential" scenario, and 3.1% under the "high price-low potential" scenario. As expected, the most favorable conditions, i.e., lowest price and highest potential scenarios, lead to better cost performances.

The results shown in Fig. 5 indicate that, at a fixed DAC price, permit allocations to the GCC countries under fair burden sharing agreements increase with available sequestration potential. Notably, this increase in allocation also occurs at reduced prices. That GCC countries generate even more permits from DAC under "low-price and high-potential" scenarios may seem counterintuitive; however, the explanation lies in the evolution of CO_2 permit prices, which are greatly reduced under the "low-price and high-potential" scenarios. Given lower permit prices, the GCC countries seek greater permit allocation to compensate for their losses. Our numerical experiments estimate the GCC budget share between 7.8% and 12.1%.

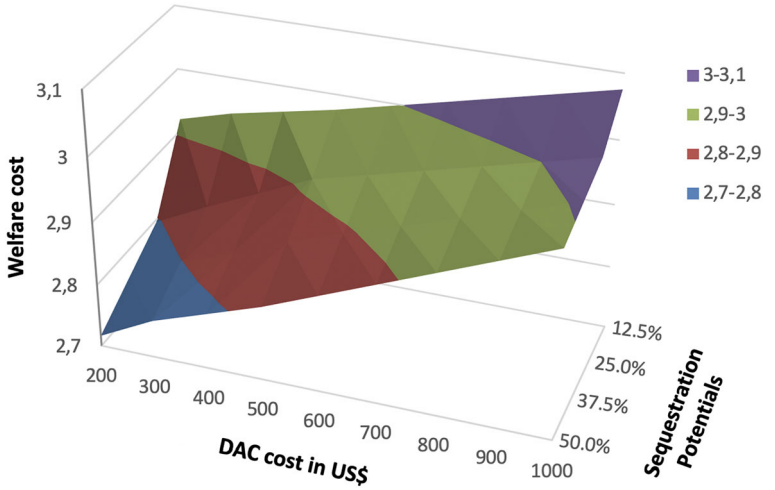


Fig. 4 Discounted global welfare cost in % of discounted GDP with respect the DAC cost and potential

5 Discussion and conclusion

This paper complements previous works (Stephan and Paterson 2012; Marcucci et al. 2017; Peterson and Weitzel 2016) in several ways: (i) it provides an assessment of GDP and welfare losses based on a general equilibrium model; (ii) it estimates the impact of CDR technologies on an international environmental agreement, represented by shares of a safety cumulative emissions budget; (iii) and it proposes a burden sharing scheme that limits welfare loss to 2.8% of cumulative discounted GDP for each of the 10 coalitions. Some new insights are gleaned from the simulations presented above: (i) a net-zero emissions regime by the end of the century is greatly facilitated by the implementation of CDR technologies, and DAC in particular; (ii) in a net-zero emissions regime under an international emissions

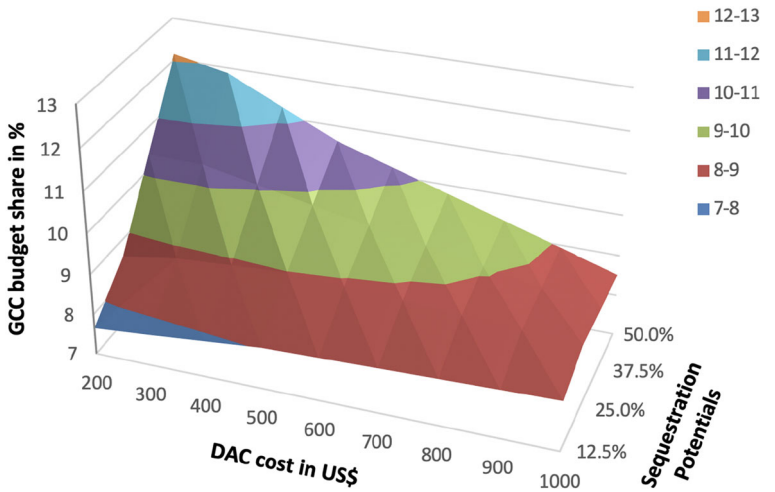


Fig. 5 Fair GCC budget share with respect the DAC cost and potential

trading market, captured CO_2 represents a new resource, with low extraction cost and tradable on the international carbon market[17]; (iii) developments in DAC technology, along with a fair allocation of allowances under an international emissions trading system, mitigate risks involved with unburned carbon among GCC countries; (iv) finally, in a world where fossil fuel reserves could become stranded assets, developments in DAC technology will help to diversify GCC economies[18]. As such, the following conclusions, summarized below, derive from the main results of the simulations:

- A market-based approach, with equalized marginal abatement costs and Rawlsian allocation of permits, yields a uniform discounted GDP welfare loss of 3.8% when no CDR option is available (see Table 2). For the GCC countries, this corresponds to a welfare loss of $5 trillion in discounted GDP[19].
- Including CDR options decreases this loss by 26% (from $5.0, to $3.7, trillion), corresponding to an equalized welfare loss of 2.8% of discounted GDP. In this process, DAC penetration first yields a significant reduction of abatement costs in all countries, and particularly for the GCC countries, falling from $7.6 trillion to $4.3 trillion. Second, DAC investments and operations—estimated at $7.1 trillion for the GCC countries—enable them to obtain additional emission permits for sale on the international market. Compensation transfers remain virtually unchanged compared with the no-CDR case, since the sale of more permits offsets lower permit prices. In brief, introducing DAC reduces unburned oil and reduces the loss of oil and gas revenues for energy exporting countries. DAC technology is therefore central to the design of a fair climate agreement: it allows GCC countries to exploit a comparative advantage associated with large natural gas endowments and high CO_2 storage capacities[20].

The investment needed for such a massive DAC capability would be around $223 billion. While these numbers are daunting, given a carbon price above $480/t after 2030, such investments represent an interesting industrial diversification, ensuring a longer life to soon-to-be-unburnable assets, at no logistical cost to valorize natural gas.

Finally, GCC member states have historically been proactive in oil and gas geopolitics. This study shows a further avenue for proactivity in climate geopolitics, should they foster

[17] In this study, we assumed that all CO_2 captured by the DAC were stored. There is indeed another potential use of the DAC to produce clean fuels that could be exported by the GCC member states or used locally in agriculture, for example.

[18] Recently, Qatar Petroleum announced a 5 million tonne CCS project for 2025. https://qp.com.qa/en/Pages/BannerAdvertisement.aspx?imgname=08102019+HE+CEO+-+Oil+and+Money+Conference+2019+English.jpg.

[19] In a market-based approach where marginal abatement costs are equalized by a uniform carbon tax designed to meet a SCEB of 1170 Gt CO_2, a welfare loss for the GCC countries close to 17% of GDP is obtained when no CDR option is available. This result, which is not presented in the paper, is provided here as an indication of the risk of unburned oil for the GCC countries. The discounted sum of abatement costs and GTT is estimated at $16.1 trillion ($7.6 trillion and $8.5 trillion for abatement costs and GTT, respectively). This GTT loss is of the same order of magnitude as the global fossil fuel rent loss estimated in Bauer et al. (2016) at $\$_{2005}$ 12.4 trillion in a 450-ppm stabilization scenario. The financial transfers due to permits selling compensate for these welfare losses and reach $11.1 trillion. They result from the allocation of the global safety emissions budget.

[20] The global carbon rent equals $290 trillion significantly higher than the one given in Bauer et al. (2016) for a 450 ppm CO_2-eq and equal to $\$_{2005}$ 32 trillion. But these discounted figures are based on a different discount factor (3% in our case and 5% in Bauer et al. (2016)) and our cumulative emission are 12% higher than their 40 ppm scenario (Using in our model a 5% discount factor and the same cumulative budget gives a global carbon rent equal to $\$_{2005}$ 112 trillion).

R&D in CDR technologies and contribute to the establishment of efficient and fair compensation mechanisms. Indeed, this study shows that, in an international emissions trading system, a coalition of the GCC countries could claim, in a fair agreement, up to 8.8% of the emissions rights from an SCEB of 1170 Gt CO_2. It is a brighter future for the GCC countries where DAC technologies penetrate at sufficient scale. While efficient capture of CO_2 with low concentration in open air remains an open research domain, we may expect large advances in terms of cost and availability. Similarly, the design of a fair burden sharing mechanism, based on allocation of a global safety cumulative emissions budget and trading on an international carbon market, falls to political science research. As suggested by the results of this study, these two research domains could become key priorities for GCC economies and other fossil fuel producing countries and companies.

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Declarations

Disclaimer The findings herein reflect the work, and are solely the responsibility, of the authors. The paper does not necessarily reflect the opinions of the European Commission.

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References

Aguiar A, Narayanan B, McDougall R (2016) An overview of the GTAP 9 data base. Journal of Global Economic Analysis 1(1):181–208

Babonneau F, Bahn O, Haurie A, Vielle M (2020) An oligopoly game of CDR strategy deployment in a steady-state net-zero emission climate regime. Environmental Modeling & Assessment, online first

Babonneau F, Haurie A, Vielle M (2016) Assessment of balanced burden-sharing in the 2050 EU climate/energy roadmap: a metamodeling approach. Clim Chang 134(4):505–519

Babonneau F, Haurie A, Vielle M (2018) From COP21 pledges to a fair 2°C pathway. Economics of Energy & Environmental Policy 7(2):69–92

Baik E, Sanchez DL, Turner PA, Mach KJ, Field CB, Benson SM (2018) Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. PNAS 115(13):3290–3295

Bauer N, Mouratiadou I, Luderer G, Baumstark L, Brecha RJ, Edenhofer O, Kriegler E (2016) Global fossil energy markets and climate change mitigation an analysis with REMIND. Clim Chang 136:69–82

Bernard A, Vielle M (2003) Measuring the welfare cost of climate change policies: a comparative assessment based on the computable general equilibrium model GEMINI-e3. Environ Model Assess 8(3):199–217
Bernard A, Vielle M (2008) GEMINI-E3, a general equilibrium model of international national interactions between economy, energy and the environment. Computational Management Science 5(3):173–206
Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M (2006) WITCH: a world induced technical change hybrid model. Energy Journal 27:13–37
Chen C, Tavoni M (2013) Direct air capture of CO_2 and climate stabilization: a model based assessment. Clim Chang 118:59–72
Consoli (2019) Bioenergy and carbon capture and storage. https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-perspective_FINAL_18-march.pdf, Global CCS Institute
Fouré J., Bénassy-Quéré A, Fontagné L (2012) The great shift: macroeconomic projections for the world economy at the 2050 horizon. Technical Report 2012-03 CEPII
Gardarsdottir SA, Normann F, Andersson K, Johnsson F (2014) Process evaluation of CO_2 capture in three industrial case studies. Energy Procedia 63:6565–6575
Gardarsdottir SA, Normann F, Andersson K, Johnsson F (2018) Investment costs and CO_2 reduction potential of carbon capture from industrial plants - a Swedish case study. Int J Green Gas Control 76:111–124
Gollier C, Tirole JMP (2015) Negotiating effective institutions against climate change. Economics of Energy and Environmental Policy 4:5–27, 1
Haurie A, Babonneau F, Edwrads N, Holden P, Kanudia A, Labriet M, Leimbach M, Pizzileo B, Vielle M (2014) Fairness in climate negotiations : a meta-game analysis based on community integrated assessment, chapter in Lucas Bernard and Willi Semmler eds. Oxford Handbook on the Macroeconomics of Global Warming Oxford University Press
Heyward C (2013) Situating and abandoning geoengineering: a typology of five responses to dangerous climate change. Political Science & Politics 46(1):23–27
House KZ, Baclig AC, Ranjan M, Nierop EA, Wilcoxx J, Herzog HJ (2011) Economic and energetic analysis of capturing CO_2 from ambient air. PNAS Early Edition, pp 1–6
International Energy Agency (2016) World Energy Outlook 2016
International Energy Agency (2020) World Energy Outlook 2020
Keith DW, Holmes G, Angelo DST, Heidel K (2018) A process for capturing CO_2 from the atmosphere. Joule 2:1573–1594
Keith DW (2009) Why capture CO_2 from the atmosphere? Science 325(5948):1654–1655
Keith DW, M Ha-Duong M, Stolaroff J (2006) Climate strategy with CO_2 capture from the air. Climatic Change 74(1-3):17–45
Koornneef J, can Breevoort P, Hendricks C, Hoogwijk M, Koops K (2011) Potential for biomass and carbon dioxide capture and storage. Technical report, International Energy Agency
Kypreos S (2007) A MERGE model with endogenous technological change and the cost of carbon stabilization. Energy Policy 35:5327–5336
Kypreos S, Bahn O (2003) A MERGE model with endogenous technological progress. Environ Model Assess 8:249–259
Lackner K (2009) Capture of carbon dioxide from ambient air. Eur Phys J Spec Top 176:93–106
Marcucci A, Panos V, Kypreos S (2017) The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. Climatic Change
McGlade C, Etkin P (2014) Unburnable oil: an examination of oil resource utilisation in a decarbonated system. Energy Policy, pp 102–12
Meadowcroft J (2013) Exploring negative territory carbon dioxide removal and climate policy initiatives. Clim Chang 118(1):137–149
Mitchell D, James R, Forster PM, Betts RA, Shiogama H, Allen M (2016) Realizing the impacts of a 1.5°C warmer world. Nature Clim Change. Advance online publication, 6, 735737 doi.org/10.1038/nclimate3055
Nabuurs GJ, Masera O, Andrasko K, Benitez-Ponce P, Boer R, Dutschke M, Elsiddig E, Ford-Robertson J, Frumhoff P, Karjalainen T, Krankina O, Kurz WA, Matsumoto M, Oyhantcabal W, Ravindranath NH, Sanz Sanchez MJ, Zhang X (2007) Forestry. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 543–584
Nemet GF, Brandt AR (2012) Willingness to pay for a climate backstop: liquid fuel producers and direct CO_2 air capture. Energy J 33(1):53–81

Paltsev S, Sokolov A, Gao X, Haigh M (2018) Meeting the goals of the Paris agreement: temperature inmplications of the Shell Sky scenario. Technical Report 330, MIT Joint Program on the Science and Policy of Global Change

Peterson S, Weitzel M (2016) Reaching a climate agreement: compensating for energy market effects of climate policy. Clim Pol 16(8):993–1010

Rogelj J, Shindell D, Jianga K, Fifita S, Forster P, Ginzburg V, Handa C, Kheshgi H, Kobayashi S, Kriegler E, Mundaca L, Séférian R, Vilarino MV (2018) Global warming of 1.5°C an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty chapter Mitigation pathways compatible with 1.5°C in the context of sustainable development

Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V, Riahi K (2015) Energy system transformations for limiting end-of-century warming to below 1.5°C. Nature Clim Change 5(6):519–527

Rubin ES, Davison JE, Herzog HJ (2015) The cost of CO_2 capture and storage. International Journal of Greenhouse Gas Control 40:378–400

Shell-Corp (2018) Shell scenarios sky: meeting the goals of the Paris agreement. Technical report, Royal Dutch Shell

Stephan B, Paterson M (2012) The politics of carbon markets: an introduction. Environmental Politics 21(4):545–562

The American Physical Society (2011) Direct air capture of CO_2 and climate stabilization: a model based assessment with chemicals: a technology assessment for the APS panel on public affairs. Technical report

United Nations (2017) World population prospects: the 2017 revision. Population Division, Department of Economic and Social Affairs

Winchester N, Reilly JM (2015) The feasibility, costs, and environmental implications of large-scale biomass energy. Energy Economics 51:188–203

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Affiliations

Frédéric Babonneau[1,3] · Ahmed Badran[2] · Maroua Benlahrech[2] · Alain Haurie[3,4] · Maxime Schenckery[5] · Marc Vielle[6]

Ahmed Badran
a.badran@qu.edu.qa

Maroua Benlahrech
maroua.benlahrech@qu.edu.qa

Alain Haurie
ahaurie@gmail.com

Maxime Schenckery
maxime.schenckery@ifpen.fr

Marc Vielle
marc.vielle@epfl.ch

1 ORDECSYS, Switzerland and Escuela de Negocios, Universidad Adolfo Ibañez, Santiago, Chile

2 Qatar University, Doha, Qatar

3 ORDECSYS, University of Geneva, Geneva, Switzerland

4 GERAD, HEC Montréal, Montréal, Quebec, Canada

5 IFPEN, IFP School, Rueil-Malmaison, France

6 École Polytechnique Fédérale de Lausanne, LEURE, Lausanne, Switzerland