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Economic assessment of the possible role of CDR technologies in long-term climate strategies for GCC Countries

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Economic assessment of the possible role of CDR technologies in long-term climate strategies for GCC Countries

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Abstract

This paper addresses the issue of assessing long-term strategies for Gulf Cooperation Council (GCC) in the perspective of the Paris agreement goal (limit to 2°C the surface atmospheric temperature increase by the end of the 21st century). In particular, one evaluates the possible role that carbon dioxide removal (CDR) technologies, allied to an international emissions trading market, could play in these strategies, as a way to mitigate welfare losses for GGC countries. To model the strategic context, one assumes that a global cumulative emissions budget has to be allocated among different coalitions of countries, GCC being one of them, and that an international emissions trading market is implemented. A meta-game model is proposed in which deployment of CDR technologies is a strategic variable and one assesses through simulations on a General Equilibrium model the possible economic impacts of their introduction.

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Key policy insights.

- GCC countries are exposed to a substantial risk of un-burnable oil and gas or stranded assets if the goals of the Paris agreement are achieved.
- The Paris agreement goals could be achieved with a welfare loss for each coalition limited to 2.8% of discounted cumulative GDP over the 2020-2100 period.
- A GCC coalition could claim in this fair agreement up to 8.8% of the emissions rights corresponding to a global safety cumulative budget of 1170 Gt CO_2.
- Investing in CDR/DAC technologies appears to be an important strategic element for GCC countries to limit or compensate revenue losses from fossil fuels.
- GCC countries could become more proactive in climate geopolitics to foster R&D in CDR technologies and contribute to the establishment of efficient compensation mechanisms, like e.g. an international emissions trading system.

Keywords. GCC countries, Climate negotiations, Carbon dioxide removal, Financial compensation.

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1 Introduction

This paper deals with an assessment of the possible mitigation of the macroeconomic cost for Gulf Cooperation Council (GCC) countries incurred if the Paris agreement goals are to be reached. In particular one considers the possible contribution of Carbon Dioxide Removal (CDR) technologies in the definition of long term strategies of GCC countries to reach these goals. The CDR technologies considered include in particular BECCS Biomass Energy with CCS (BECCS) and Direct Air Capture (DAC). GCC countries[1] economies, largely based on oil and gas revenues, could be strongly affected

[1] Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

in a worldwide drive toward a net-zero emissions regime, which is implicit in the Paris agreement. This objective could be reached by 2070 or even 2050 as discussed in the COPs 22 to 24.

The current stance of GCC countries, in particular Saudi Arabia, which resist an international drive toward a more rapid global abatement expose them to a very high stranded asset risk. A recent IPCC report [38] presents several emission trajectories proposed by different integrated assessment models to abide to Paris-agreement objectives. They all consider 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 [41], 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 negative-net emissions, a profound transformation of the energy system is proposed in the Sky scenario. In 2070, solar counts for 32% of primary energy source, wind for 13 %. Oil, natural gas and coal count for 22 % and are associated with Carbon Capture and Storage (CCS). Bioenergy counts for 14% and is also associated with CCS. Biomass Energy with CCS (BECCS), which consists in a biomass-based combustion power plant with CO_2 capture, is the negative emission technology of choice. It pumps CO_2 out of the atmosphere while producing electricity. A drawback of choosing BECCS as the main technology generating negative emissions is the logistics of production and transport of biomass feedstock, which will enter in competition with food production and afforestation/reforestation [47]. This imposes stringent limits on a massive deployment of BECCS.

Another option, much costlier than BEECS but which could be of strategic importance to GCC countries is offered by Direct Air Capture (DAC). Recently several scenarios for a global long term strategy to comply with the Paris agreement have been proposed, where DAC appears as a promising technology for the attainment of a net-zero emissions regime [30]. In [27], the model MERGE-ETL [23, 22] is used to show that DAC technology can play an important role in realizing deep decarbonization goals and in the reduction of regional and global mitigation costs with stringent targets. In the 2°C and 1.5°C scenarios analyzed DAC technology captures 21 and 40 $GtCO_2$ in 2100, respectively. A net-zero emissions regime is attained in 2075 and 2040 respectively, and very large negative emissions occur at the end of the planning horizon. It is difficult to imagine how these scenarios could be implemented, given the current fracture existing among different participating countries, the decision by USA to quit, the reluctance of industrialized countries to pay for the transition in LDCs. It is also difficult to see precisely what would be the advantage for GCC countries to participate actively to such a global long term strategy. In this regard, a recently published paper [20] gives a complete feasibility and techno-economic assessment of a DAC technology. The technology is fully based on natural gas for providing needed power and heat As such it could have an important comparative advantage in the development of DAC technologies in gas producing regiopns. By transforming their natural gas endowment and sequestration capacity in depleted oil and gas reservoirs, into negative emissions, GCC countries could have access to a new resource, which could have a high economic value when considering the implicit price of carbon which is associated with the above mentioned long term global strategies. Thus, this paper is devoted to an assessment of the macroeconomic consequences of introducing CDR technologies and in particular DAC for GCC countries into the international climate policy and negotiation design.

To evaluate potential macroeconomic costs of long-term climate strategies implemented by different groups of countries (coalitions sharing the same level of development), we use a meta-game model, which is more fully described in [3]. It represents a possible competition on an international market of emissions rights of 10 groups of countries, GCC being one of these coalitions. In the model one assumes a transition toward a net-zero emissions climate regime with a limited cumulative emissions budget over the period 2020-2100, which is compatible with a 2°C warming by 2100. International cooperation is represented by an agreement on sharing the remaining cumulative emissions budget[2], and the financial transfer mechanism supposed to be implemented in the Paris agreement is represented by trading permits on an international market for emission rights. The optimal exploitation by each coalition of its share of the emissions budget is given by a Nash equilibrium in a dynamic game model. Using this framework, we can provide a first assessment of the contribution of CDR technologies to lowering the global mitigation cost and providing some comparative advantages to GCC countries in the future long term climate regime.

The paper is organized as follows. In section 2, we first discuss the history of GCC participation in the Paris agreement, their attempt to define a long term climate strategy and we summarize the method used for a macroeconomic evaluation. In section 3, we present numerical estimations and look,

[2]A safety cumulative emissions budget of 1 trillion ton carbon has been shown to be compatible with the 2°C goal [38]

in particular, at the potential impact of developing DAC technologies on the compensation that GCC countries could claim in a fair climate agreement. In Section 4, we discuss policy implications and Section 5 concludes.

2 Context and proposed approach

In this section we first look at the context in which the GCC countries have to envision a worldwide transition to net-zero emissions climate regime. Then we present the macroeconomic and game theoretic evaluation tool that is used for our assessment.

2.1 Paris agreement and GCC countries

The goal affirmed in the Paris agreement is to limit the global warming below 2°C in 2100 (or even below 1.5°C). Regarding mitigation aspects, each party (i.e. country) is supposed to propose a binding commitment, called nationally determined contribution (NDC) and communicate the measures that will be implemented to attain these objectives (article 4). The agreement allows the possibility of voluntary cooperation within the market and non-market approaches among countries in both mitigation and adaptations strategies (article 6). The Paris agreement also reaffirms the need for cooperation between developed and developing countries through a Green Climate Fund (article 9)

The long-term goal established by UNFCCC in Paris, and reaffirmed in the subsequent COPs implies reaching a global zero net emissions regime as demonstrated in the last IPCC reports and several integrated assessment models (e.g. [33]). In this context, the climate negotiations will aim at reducing drastically fossil fuels consumption and as a consequence would seriously impact the energy exporting countries economies [28]. GCC countries have joined the Paris agreement. They operate within the Arab Group[3], which is their primary negotiating bloc. While some coordination takes place among the six GCC countries, this group has always been fragmented. This fragmentation has grown as a result of the economic embargo placed on Qatar by some other GCC members since 2017. However GCC is, by definition a cooperation council for countries that share the same risks and same interests in the forthcoming negotiations. In the context of these forthcoming

[3]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.

negotiations it may be thought that the Gulf Cooperation Council will tend to play its role and manage to defend the interests of its member states. This may justify the consideration of the GCC as a coalition or group in the UNFCCC. The INDCs that the parties to Paris agreement have proposed are notoriously not sufficient to attain the 2°C goal. There is a need to define a road map for reaching the goals of the agreement, as done e.g. in the IEA Sustainable Development scenario [17] or the Shell Sky scenario [41]. An efficient way to coordinate the efforts of the countries could be achieved through implementation of a uniform carbon tax or an international carbon market based on a cap and trade mechanism (see Tirole and Gollier paper [13]). 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. This may appear highly unlikely, in the context that has been just described. However this provides a benchmark, since the situation described in this study 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 GCC countries.

Although GCC countries account for less than 2.4% of GHG emissions[4], global climate change will have a severe environmental impact on the region. Rising temperatures will affect agriculture and water resources as well as power generation with an increasing cooling demand [36]. In addition, many environmental challenges including desertification, biodiversity loss, water scarcity and sea level rise will make it difficult for GCC countries to continue their unsustainable environmental and economic practices.

For several decades, the socio-economic development of GCC countries has relied almost exclusively on the revenues from oil and natural gas exports. The wealth in hydrocarbon natural endowments have even encouraged GCC countries to invest in energy intensive industries and infrastructure. Domestically, the policies of low energy prices have yielded overconsumption patterns in the local population. As an example, Qatar has one of the largest per capita carbon footprint in the world[5]. Adhering to the target of 2°C level of global warming at the end of the century, set by the Paris agreement, means that GCC countries have to reduce the level of GHG emissions by implementing a transition towards new clean energy systems.

[4] Calculation based on https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?name_desc=false

[5] Reaching in 2014, 45.42 metric tons per capita in Doha [10].

On the other hand if the UNFCCC negotiations succeed in imposing a transition to a net-zero emissions regime, the GCC countries will have to curb the export of oil and natural gas, with a strong impacts on their export revenues, their future development plans and finally on the welfare of the population. From a political economy perspective, moving away from fossil fuel revenues means changing the nature of the social contract between governments and GCC populations[6].

GCC countries are thus exposed to the risk of "un-burnable" fossil fuels and stranded assets. It has been evaluated that for reaching the 2°C objective, up to a third of oil reserves and half of gas reserves could remain unused by 2050 [29]. For the Middle East, 38% of existing reserves of oil and 61% of natural gas could be stranded. Indeed, the question of un-burnable oil is at the top of the agenda of the energy transition for oil and gas producing countries [37]. In the framework of UNFCCC, compensation for oil left in the ground was first proposed by Ecuador in 2012 [26]. This idea has gained momentum when Gulf states understood that revenue losses from reduced demand, low prices, oil rent loss and trade barriers are the near term consequences of a loss of wealth from the potentially stranded oil and gas assets [18]. The total value of stranded assets across upstream energy, power generation, industry and buildings is found to reach $20 trillion, approximately 4% of global wealth. Stranded assets for upstream energy are evaluated at approximately $7 trillion under the Delayed Policy Action scenario [18]. Any large capital investment in upstream infrastructure would result in significant stranding after 2030. A study in [42] using a KLEM model for Saudi Arabia demonstrates that the oil rent cannot remain the only source of public income. Other related studies discuss the situation of GCC countries and in particular stranded asset issues [32, 44, 19, 25, 8, 9, 34, 2].

2.2 The proposed modeling approach

We adopt a model, more fully described in [3], that can provide a first insight on the possible mitigation of welfare losses of GCC countries through implementation of a long term global strategy where penetration of CDR technologies and participation in an international emissions trading system play an important role. The model describes the competition among 10 coalitions of countries, GCC countries forming one of those, in the supply of emissions permits on an international cap and trade system that is designed

[6]For long, this contract was built on the model of the rentier state wherein the revenues from selling oil and gas were used to cater for the increasing demands from local populations for modernity and economic and social development [37].

to satisfy a global safety emissions budget, evaluated at 1170 GT of CO_2, over the period 2020-2100 and reach a zero-net emission regime at the end of this period. In the climate negotiations the share of the emissions budget that goes to each coalition is decided. The coalitions play a noncooperative game in the supply of emissions permits on the market. Depending on their respective abatement policies, the coalitions can be net buyer or net seller of permits. This generates payment transfers that contribute to the attainment of a fair burden sharing. The different components of this model are presented below.

2.3 Macroeconomic analysis based on an extended GEMINI-E3 model

The analysis is based on a version of the CGE model GEMINI-E3 [5] specifically designed to assess the impact of climate change mitigation policies on GCC countries and stranded fossil fuel assets. The current version is built on the GTAP 9 data base [1], with reference year 2017. In this version, we detail 10 groups of countries (regions or coalitions) GCC countries being one of them, as shown in Table 1. To analyze the impacts of climate change mitigation policies on stranded fossil fuel assets, we describe the extraction of fossil fuel energy according to their carbon content. 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 transits via two main channels: (i) Fossil fuel resources localized in energy exporting countries lose their value and the energy rents associated to these resource decrease, with a direct negative impact on welfare for countries that own these resources; (ii) Capital that has been already invested in energy sectors (coal mining, refineries, pipelines infrastructure) and sector energy intensive industries is depreciated, which in turn negatively impacts the households that own these assets.

GEMINI-E3 runs on the 2011-2050 period and is extended up to 2100 assuming a *steady growth* approach as explained in [3]. This macroeconomic model reproduces historical emissions 2011 to 2018 and its medium term forecast is based on the WEO outlook 2016 [16]. The economic impact of mitigation policies on energy exporting countries (like GCC countries) is measured by the loss in terms of trade representing the decrease of energy exporting revenues for these countries. These two components of welfare (GTT and Abatement cost) are used to calibrate the payoff functions in the game model that will be described in Section 2.5. From a sample of GEMINI-E3 runs, we perform econometric estimations of these gains (or losses) of terms trade (GTT) as well as the domestic abatement costs[7] to obtain the desired payoff functions.

2.4 Techno-economic analysis of CDR options

The potential role of DAC in climate stabilization has been explored in [7], using the WITCH model [6]; the comparative advantage of Middle East and energy exporting countries for DAC deployment was already signaled. The same comparative advantage was observed in [27], in a study of the potential of DAC technologies based on using the MERGE-ETL model [22]. The total quantity of CO_2 captured by DAC and other carbon capture technologies is constrained by the potential of CO_2 storage in the different regions. Estimates of these storage potentials, including deep saline aquifers, hydrocarbon fields and coal beds are derived from [27] and are given in Table 1. For technical, accessibility and social acceptance issues among others, we assume that, by 2100 only a fraction (between. 25% and 50%) of these potentials can be used for DAC and BECCS operations. We also assume that DAC technologies will be mature enough for massive deployment in 2040 with a linear deployment trend afterwards.

For the cost of DAC, we rely on a recent publication [20], where a process fully powered by natural gas is described and economically assessed. The levelized cost computed by [20] is 232 \$/t-CO_2 captured, whereas the American Physical Society study [45] proposed a levelized cost of 550 \$/t-CO_2. In [15], the cost for powering a DAC plant using a natural gas-fired plant with CCS was 396 \$/t-CO_2 avoided. The extra energy cost of DAC was estimated around 232 \$/t-CO_2 captured, based on [24] and [11, 12]. The storage cost has been evaluated in [40] to be in the range of 6 to 13 \$/t-CO_2 stored. The total levelized cost shown in Table 1, will thus be set at \$300/t-CO_2 captured and stored for all regions, except for USA and EUR where we put it at \$350/t-CO_2 captured and stored, assuming a higher cost of logistics.

[7] evaluated through the deadweight loss of taxation (DWL) [4].

Table 1: Carbon storage potential in $GtCO_2$ and DAC costs in $/t-$CO_2$

		Storage potential	DAC cost
EUR	European Union (28 countries)	24.0	350
USA	United States of America	37.5	350
CHI	China	30.5	300
IND	India	20.0	300
GCC	Gulf Cooperation Council	126.5	300
RUS	Russia	86.0	300
ASI	Rest of Asian countries	23.0	300
OEE	Other energy exporting countries	46.0	300
LAT	Latin America	40.5	300
ROW	Rest of the World	23.0	300
	World	447.0	

Regarding BECCS, we consider the standard technology that consists in producing electricity from biomass while capturing and injecting CO_2 into geological formations. We use a unique levelized cost of 60$/t-$CO_2$ for the whole world, consistent with the IEA estimates [21].

2.5 Evaluation of fair compensations to GCC countries

To assess the economic consequences of a proposed climate agreement, one must assume that an optimal use of the global emissions budget will be made, or, at least that a second best solution should be reached, corresponding to a Nash equilibrium among the parties. We assume that there is a safety cumulative global emission budget (SCEB) over the time horizon 2016-2100 of 1170 Gt of CO_2. Climate negotiations, in one form or the other will bear on the sharing of this global safety emission budget among an ensemble of coalitions regrouping countries with similar macroeconomic structure. We also assume that there will exist an international emissions trading system. The coalitions will thus supply permits on the market, using strategically their share of the cumulative safety emissions budget and their abatement policies. Through the development of CDR activities like BECCS and DAC, a coalition can replenish or increase its own emission budget. In this game, the payoff to a player/coalition is obtained from the macroeconomic cost of the abatement policies, the cost of developing CDR technologies, the gains in the terms of trade (GTT) due to the global impact on world energy prices and the financial gains or losses due to permit trading. A Nash equilibrium is computed for this dynamic game. When a coalition has a levelized cost of a CDR technology, BECCS or DAC, that is lower than the permit price, then it can invest in this technology to increase the permit allowance and gain advantage in the equilibrium solution. 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 GCC countries the financial transfers through the market due to the selling of permits will generate a compensation for unburnable oil.

3 Simulation results

3.1 The reference scenario

A BAU scenario is built, using GEMINI-E3, for the period 2017–2050 and is calibrated on the "New Policies" scenario from the World Energy Outlook 2016 [16]. The BAU scenario is extended for the 2050-2100 period as described in [3]. Demographic assumptions are based on the "median variant" scenario done by United Nations [46]. World population increases by 50% from 2016 to 2100 and reaches 11.2 billion inhabitants in 2100. On the same period, global GDP is multiplied by 7 representing a 2.4% annual growth rate. In the BAU scenario, 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 can be interpreted as the rarefaction of fossil energies in the second part of the 21st century. According to this scenario, more than 4.11 trillion tons of CO_2 are emitted during the 21st century. Such an emissions budget would lead to more than 3.5°C increase of SAT w.r.t 1850-1900 period, with probability 66% (see [38]).

3.2 Impact of CDR activity in global mitigation scenarios

We consider two scenarios involving an SCEB of 1170 Gt of CO_2 on the period 2016-2100, without and with CDR technologies. This budget is consistent with the recent IPCC report [38] on pathway to 2°C. We assume that very stringent climate policies can be implemented only after 2030.

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

Without CDR more abatement is required and CO_2 emissions have to converge to zero level at the end of the 21stcentury. A significant welfare cost of 3.8% of the discounted GDP on the 2018-2100 period. When DAC and BECSS are used the worldwide welfare cost is reduced to 2.8%. Without CDR technologies, the CO_2 price is equal to 776$ in 2030 and reaches 4140$ in 2100 showing the stringency of climate target when these technologies are not available. With CDR technologies, the CO_2 price is equal to 480$ in 2030 and reaches 1292$ in 2100. These figures are consistent with the ones given in the special report of Global Warming of 1.5°C done by IPCC [38]. Indeed the range estimates of IPCC report under a Higher-2°C pathway are equal to 15–200$ in 2030 and 175–2340$ in 2100.

Figure 2 represents the same two mitigation scenarios showing the contribution of DAC and BECSS.

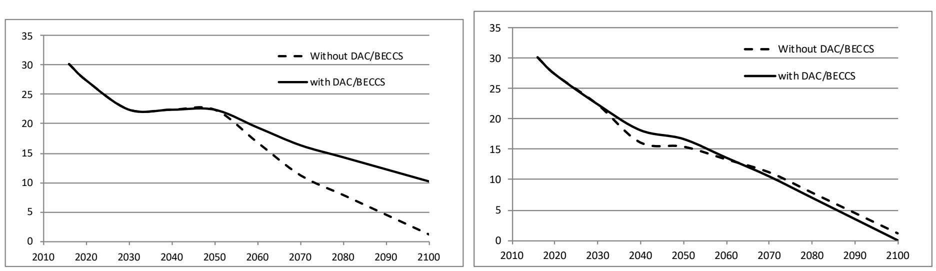

Figure 1: World total emissions (left) and net emissions (right) in Gt CO_2

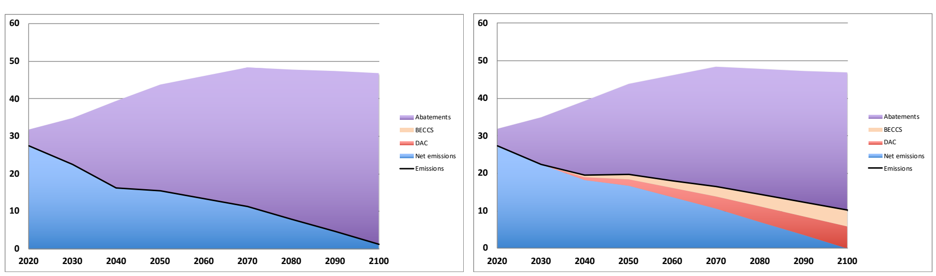

Figure 2: Net emissions, DAC, BECCS and abatement profiles without (left) and with (right) DAC/BECCS

Figure 3 shows the variation of global welfare cost with the SCEB target in scenarios permitting 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 [39, 31], with a cost multiplied by 5.

Table 2: CO_2 price and welfare cost 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%

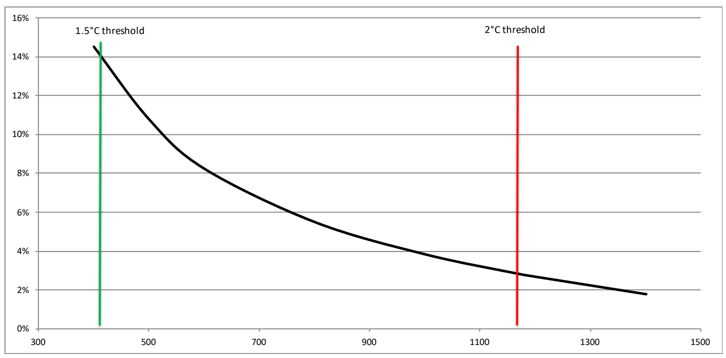

Figure 3: Discounted global welfare cost in % of discounted GDP with respect to carbon budget in Gt CO_2

To complement this analysis, we have also simulated a scenario in which one assumes full cooperation between all nations. One assumes that a policy which minimizes the total cost for the whole world, without any constraints on the timing of abatements is implemented. In this "utopia" scenario the global percentage loss of GDP decreases from 2.8% to 2.1%. This shows that the scenario with second best solution is not too far away from global optimality.

3.3 Fair allocation of SCEB to GCC countries

Prior to designing possible fair sharing agreements, we assess first the economic impacts of implementing two common quotas allocation rules extensively discussed and analyzed in the literature, i.e., "Grandfathering" and "Per Capita". Table 3 shows the budget shares and welfare losses for these two rules. The first rule considers that the allocation of quotas is proportional to emissions on the whole period (2016-2100) in the BAU scenario. This sovereignty principle is usually proposed as a starting point in environmental negotiations taking into account the existing situations. Energy exporting countries (Russia, GCC countries and OEE) and Rest of the

World[8] incur a very high burden whereas India, Latin America and China benefit largely from this allocation. The second rule assumes that the budget share is proportional to the population over the period 2016-2100. This equalitarian rule gives a large number of extreme welfare impacts. The most populated countries earn significant revenues coming from emissions selling. Therefore, India, rest of the World and Latin America experience welfare improvement after implementing the climate mitigation policy. In contrast, energy exporting countries but also China and USA bear a huge welfare cost.

In both cases, fairness is not achieved and GCC countries are strongly disadvantaged with 11% and 13.8% of discounted GDP losses. Indeed, the small amounts of permits allocated to GCC countries, i.e., 2.9% for the Grandfathering rule and 0.9% for the Population rule, appear to be largely insufficient to compensate their revenue losses on world energy markets.

Table 3: Budget shares and welfare losses for two allocation rules

	Grandfathering		Per Capita	
	Allocation in %	Welfare cost[a]	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

We address now the issue of a fair allocation of the SCEB, following the approach proposed in [3]. A burden-sharing rule is proposed, which equalizes the welfare losses among the 10 groups of countries. This rule is called "Rawlsian" allocation, as it tends to maximize the worst affected welfare. Table 4 displays the resulting fair allocation of quotas and the cost decomposition among abatement, DAC and BECCS activities, GTT and permit exchanges on the international emission market.

These results are complemented by a sensitivity analysis to evaluate the impact of the DAC costs and potentials to the burden sharing agreement. We define a set of scenarios considering DAC potentials between 12.5% and

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

Table 4: Burden-sharing and welfare cost with Rawlsian rule

	Budget share	Welfare cost[a]	Components of welfare cost[a] Abatement	DAC	BECCS	GTT	Exchange[a]
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 GDP
[b] Negative (positive) values are for net sellers (buyers)

50% of the sequestration potentials and DAC costs on the range 200 to 1000 US$ per ton of CO_2 sequestered. In Figures 4 and 5, we display the discounted global welfare cost in % of discounted GDP and the fair GCC budget shares, respectively.

We observe on Figure 4 that the welfare cost varies reasonably between 2.7% for the “low price-high potential” scenario to 3.1% for the for the “high price-low potential” scenario of the total discounted GDP. As expected, the most favorable conditions, i.e., lowest price and highest potential scenarios, lead to better cost performances.

The results shown on Figure 5 indicate that for a fixed DAC price, permit allocations for GCC countries in fair burden sharing agreements increase with the available potential. The allocation also increases for reduced prices. This result may look counterintuitive as GCC countries generate even more permits from DAC in “low-price and high-potential” scenarios. Indeed, the explanation is in the evolution of CO_2 permit prices that reduces strongly for the “low-price and high-potential” scenarios. Since the permit prices are lower, GCC countries need more permit allocation in the agreement to compensate their losses. We estimate in our numerical experiments a range of 7.8% to 12.1% for the GCC budget share.

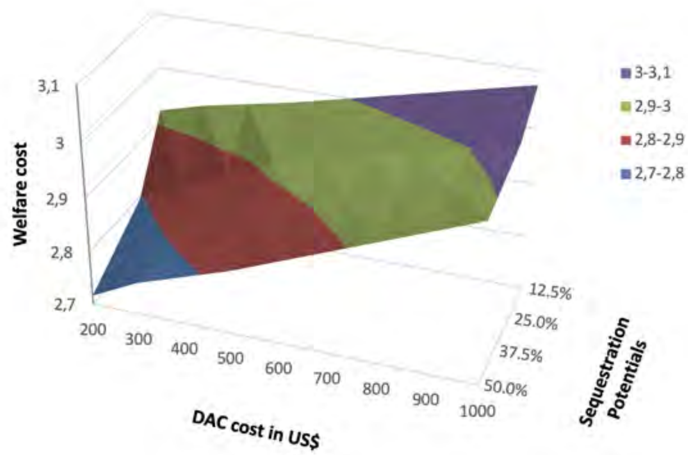

Figure 4: Discounted global welfare cost in % of discounted GDP with respect DAC cost and potential

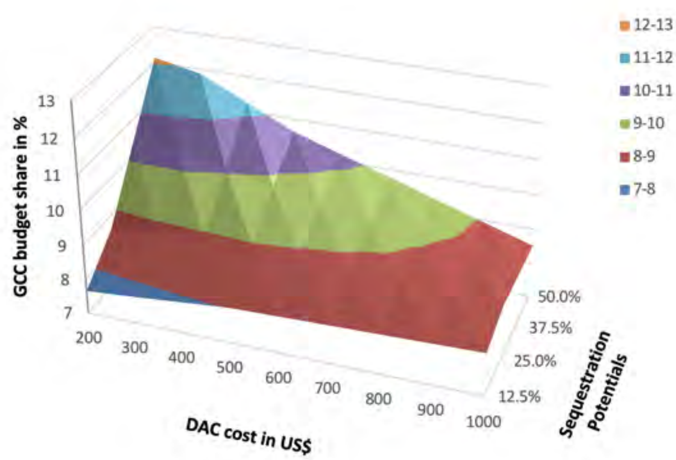

Figure 5: Fair GCC budget share with respect DAC cost and potential

4 Discussion

From the scenario simulations presented above one can draw the following insights: (i) CDR and in particular DAC technologies are necessary to reach a net-zero emissions regime by the end of the century; (ii) In a net-zero emissions regime with international emissions trading market, the captured CO_2 becomes a new resource priced on an international market for emission rights with no logistical cost[9]; (iii) DAC technology development and quota endowment in an international emissions trading system could contribute to mitigate stranded asset risks; (iv) In a world where fossil fuels could become un-burnable DAC technology development could contribute to diversification of the GCC countries economy[10].

In a solution in which marginal abatement costs are equalized among coalitions (Rawlsian rule), without CDR options, our simulations show that an SCEB of 1170 Gt CO_2 implies a GDP loss of 6.5% for GCC countries due to the changes in the terms of trade, representing \$7.4 trillion in discounted sum of GDP over the 2020-2100 period. The discounted cost of abatement is estimated at \$7.1 trillion. The transfer to balance these welfare losses would attain \$10 trillion resulting finally in a welfare loss 3.8% of discounted GDP for the GCC coalition (see Table 2) or \$4.7 trillion.

When considering the CDR option, this loss reduces by 45% (from \$4.7 to \$2.6 trillion), which corresponds to an equalized 2.8% of discounted GDP. First, DAC penetration permits a significant decrease of abatements and as a consequence of the abatement cost for all countries, in particular for GCC countries, from \$7.1 to \$3.7 trillion. Second, the DAC investments and operations, estimated to a \$2.3 trillion cost for GCC states, provide them with additional emission permits exploited on the international trading market keeping almost unchanged transfer compensations. In fact, DAC implementation would burn the equivalent of 7-13% of GCCs natural gas proven reserves. The DAC technology appears thus as a key parameter in the design of an efficient climate agreement and allows GCC countries to exploit a comparative advantage associated with large natural gas endowments and strong CO_2 storage capacities.

Given their low lifting cost for oil and gas, GCC countries will probably

[9] In this study, we assumed that all CO_2 captured by DAC was stored. There is, indeed another potential use of DAC to produce clean fuels that could be exported by GCC member states.

[10] recently QP announced the project of CCS for 5 Millions Tons by 2025 `https://qp.com.qa/en/Pages/BannerAdvertisement.aspx?imgname=08102019+HE+CEO+-+Oil+and+Money+Conference+2019+English.jpg`.

be the last to produce fossil fuels to supply industries which structurally have to use hydrocarbons (e.g., petrochemicals, fertilizers, marine and plane transportation, and other niches in energy intensive activities). These industries will emit CO_2 that will be captured and sequestered at the pace given by the price of CO_2 emission trade. To continue to invest in these industries with abatement mechanisms is a simple continuation of the current industrial diversification implemented by GCC countries in a context of zero-net emission. For instance, Qatar Petroleum has announced a new CCS project to capture carbon from its planned LNG trains expansion. Carbon will be injected to enhance oil recovery in close by mature oil fields. Abatement strategies including new efficient technologies and CCS projects are then implemented at the same pace that the price of the CO_2 emission raises.

In a zero net emission regime with international emission trading market, the captured CO_2 becomes a new resource priced on an international market for emission rights. The DAC technology enables mitigation of carbon emissions of hydrocarbons wherever they are used globally. Emission of natural gas burning is compensated by capturing an equivalent amount of CO_2 from the atmosphere. For instance, using the parameters from [20] Qatar would have to burn 46 Bcm of natural gas in a DAC process to compensate for the carbon emissions of its 104 Bcm export of LNG. The investment needed for such a massive DAC capability would be around \$223 billion. These numbers are huge but in a context of a carbon price above \$480/t after 2030, they represent an interesting industrial diversification to insure a longer life to soon to be unburnable assets. This of course could represent an interesting industrial diversification with no logistical cost to valorize natural gas.

5 Conclusion

The results obtained in this study complement the work of [43, 27, 35] in several ways: (i) the assessment of GDP and welfare losses is based on a General Equilibrium Model; (ii) the impact of CDR technologies on an International Environmental Agreement, represented by the sharing of a safety emissions budget, is estimated; (iii) a possible agreement limiting the welfare loss to 2.8% of discounted cumulative GDP for each of the 11 coalitions of countries is proposed.

Historically, GCC member states have been proactive in the oil and gas geopolitics. This study shows that they could also become proactive in climate geopolitics by fostering R&D in CDR technologies and contributing to the establishment of efficient and fair compensation mechanisms. Indeed, this study shows that in an international emissions trading system, a coalition of GCC countries could claim in a fair agreement up to 8.8% of the emissions rights corresponding to an SCEB of 1170 Gt. A brighter future for GCC countries could happen if DAC technologies penetrate at sufficient scale. Efficient capture of CO_2 with low concentration in open air remains an open research domain and we may expect big advances in terms of cost and availability. Similarly, the design of a fair burden sharing mechanism based on allocation of SCEB and trading on an international carbon market is also an object of political science research. As suggested by the results of this study, these two research domains could be become key priorities for GCC economies.

A Model formulation

We report in this section the mathematical formulation of the meta-game model used in this paper to design and assess burden sharing agreements.

A.1 Model's equations

Variables and parameters

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

This expression can also be rewritten

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

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

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

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

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

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

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

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

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

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

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

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

where

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

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

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

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

A.2 Nash equilibrium conditions

We write now the first order conditions for a Nash equilibrium solution. The existence of a solution is implied by the convexity of the cost functions. Denoting $\nu_j(t)$ the K-T multiplier of the emission budget constraint (3) for coalition j, we may write the Lagrangian for each player j as given by

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

Complementarity conditions for $\omega_j(t)$

$$0 \leq \beta_j^t \frac{\partial}{\partial \omega_j(t)}[\pi_j(\tilde{\mathbf{e}}(\Omega(t), t) - \tilde{p}(\Omega(t), t)(\omega_j(t) - e_j(\Omega(t), t))] + \nu_j \tag{13}$$

$$0 \leq \omega_j(t) \tag{14}$$

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

Developing the expression

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

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

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

Complementarity conditions for $v_j(t)$

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

Complementarity conditions for $\nu_j(t)$

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

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