OPEC Oil Pricing Strategies in a Climate Regime: a Two-Level Optimization Approach in an Integrated Assessment Model

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Abstract: This paper presents an analysis of the optimal oil production quotas of OPEC under a worldwide climate regime imposing a limitation on the radiative forcing. The analysis is conducted using a multi-region detailed energy-economy-environment bottom-up model (TIAM) where the demand laws for oil and its substitutes are implicitly defined as the result of a global supply-demand equilibrium in the World energy system, including the trading of energy forms and emission permits. In this respect the analysis differs fundamentally from previous representations of OPEC options in a climate regime, since it takes explicitly into account the technology switches that will be triggered by a proactive climate policy at the World level. The analysis shows that OPEC's quota strategies have a strong impact on oil prices with *(climate scenario)* and without *(reference scenario)* a world climate regime, but OPEC's market power, measured as the impact on global welfare, remains moderate, and consequences of OPEC's quotas on emissions and climate are very limited. In the climate scenario, OPEC would derive no advantage in flooding the oil market: the severe climate target is more important in determining oil demand than OPEC's production strategies. However, OPEC's quotas slightly reinforce (positively) the energy and technology decisions taken to mitigate the greenhouse gas emissions. Finally, OPEC's profits being lower in the climate scenario compared to the reference scenario, OPEC may be reluctant to engage in a strict global emission reduction agreement (considering a decision based on oil profits alone).

Résumé: L'objectif de l'étude présentée est l'analyse de quotas de production optimale de pétrole par l'OPEP, dans le cadre d'un accord mondial de lutte contre les changements climatiques. L'analyse est réalisée en utilisant un modèle technico-économique mondial (TIAM) qui permet de représenter de manière explicite les changements technologiques nécessaires à la satisfaction des objectifs de lutte contre les changements climatiques. L'étude montre que les stratégies de production de l'OPEP ont un impact important sur les prix du pétrole, qu'il y ait accord mondial sur les changements climatiques (scénario climatique) ou pas (scénario de référence). Toutefois, le pouvoir de marché de l'OPEP, mesuré par son impact sur le bien-être total, reste modéré, et les impacts des stratégies de l'OPEP sur les émissions et le climat restent limités. Dans le scénario climatique, l'OPEP ne tire aucun avantage à « inonder » le marché en augmentant sa production : la contrainte climatique a plus de poids que les stratégies de production de l'OPEP. Néanmoins, les quotas de production limités de l'OPEP renforcent (positivement) les décisions prises ou à prendre pour atténuer les émissions de gaz à effet de serre. Finalement, l'accord climatique faisant baisser les profits de l'OPEP en comparaison au scénario de référence, l'OPEP pourrait être réticente à s'engager dans un tel accord (en considérant sa décision fondée seulement sur les profits tirés des exportations de pétrole).

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1 Introduction

Projecting the price of oil over long-term horizons is a crucial issue of the modeling and analysis of the world energy system. On the one hand, considering it as the result of a competitive market is obviously unsatisfactory since it would lead to prices that are low compared to the real market. On the other hand, the definition of the strategic behavior of the Oil Producing and Exporting Countries (OPEC) raises the question of the OPEC reaction to the establishment of a global climate regime with stringent greenhouse gas (GHG) emission abatement: Will OPEC *increase* its quotas and thus provoke a decrease of oil prices in order to induce a rebound of global oil demand? Or will the worldwide demand for oil be already so much reduced that the residual oil consumption is fairly incompressible (i.e. destined for uses that are very difficult to substitute with other fuels) and OPEC would then *decrease* its quotas (and thus increase oil prices) so as to take full advantage of the ‘captive’ residual oil demand?

The aim of this paper is to integrate and evaluate such strategic behaviors of OPEC in TIAM [11, 12], an integrated model that combines the bottom-up TIMES model and a climate module which permits the consideration of constraints on long term climate change. For that purpose, we propose to define the world price of oil endogenously, as the result of equilibrium in a hierarchical game where OPEC announces its production quotas and the rest of the world adjusts as a “competitive fringe” while taking into account a stringent carbon constraint. This corresponds to a Stackelberg game between a leader and a competitive fringe, a situation largely explored in industrial economics in general and in the analysis of the oil market in particular. This is very much in the spirit of the seminal paper by Pindyck [15,16] where the cartel is treated as “a pure monopolist holding a known quantity of reserves and facing a “net demand” function (total world demand minus supply by “competitive fringe” producers who are not members of the cartel)”. Another game theoretic approach, following Salant [18] uses a Nash-Cournot equilibrium to represent the competition between OPEC and the other oil producers; this is the case for the recent analyses of the OPEC strategies using aggregated economic "top-down" models [1, 2, 4, 10] with an open-loop information structure and where demand laws for oil and its substitutes are known. In [6], a simple two-level optimization model and an extensive game formulation have been used when the demand laws for oil, gas and coal were obtained from simulations performed with a World CGE1 (GEMINI-E3 [3]). These analyses remained unconclusive because in the context of climate change policies it is important to take into account the technological changes induced all over the energy system by the variations of the relative prices of fuels depending on their carbon content. This is made possible by using bottom-up models like MARKAL, TIMES or TIAM.

The modeling and evaluation with TIAM of different conjectures about OPEC’s behavior with and without a global climate regime show that although OPEC’s quota strategies have a strong impact on oil prices with and without a world climate regime, OPEC’s market power remains moderate, in the sense that the impact of OPEC’s quotas on global welfare stays moderate. More specifically, OPEC would derive no advantage in flooding the oil market in the Climate scenario, since its own net revenues would decrease in such an event. In other words, the severe climate target is more important in determining oil demand than OPEC strategies, and thus decreasing oil prices does not induce a sufficient demand rebound to overcome the lower price. Moreover, if OPEC’s exports are relatively insensitive to whether or not the world adopts a strict climate policy (the oil production is reduced in non-OPEC countries in the climate scenario), OPEC’s profits are lower in the Climate scenario. Thus, based on oil profits alone, OPEC may be reluctant to engage in a strict global emission reduction agreement. Finally, OPEC strategies have almost no impact on the global emissions and climate with and without a climate constraint, while they reinforce the energy and decisions resulting from the climate target.

The paper is organized as follows: in section 2, we discuss the hierarchical game structure that we propose to represent the dynamics of the world oil market; in section 3, we describe how this structure is implemented in TIAM; in sections 4 to 6, we present and analyze the results obtained with and without climate agreement; section 7 concludes the paper.

2 Conjectures on oil pricing and OPEC quotas

Since its creation, the OPEC cartel has been holding regular meetings at which production quotas by its members are recommended. Implementing oil production quotas by OPEC countries has the effect of inducing non-OPEC oil producers to adjust their own production levels in order to satisfy global oil demand.

In its streamlined form, this mechanism is strongly reminiscent of a Stackelberg quantity game with OPEC as a *leader* and non OPEC producers (plus oil consumers) as *followers*. In such a game, oil price is not directly controlled by OPEC. Rather, it is the result of the auctioning process that takes place between consumers and suppliers. Given the fact that OPEC production costs are known to be lower than production costs in non-OPEC countries, and given enough supply flexibility of the non-OPEC producers, plus the fact that there are many oil consumers, it is reasonable to conclude that the price of oil is established as the equilibrium price of a competitive supply-demand equilibrium between consumers and non-OPEC producers, with the OPEC production quotas taken as fixed. This is illustrated in figure 1. If OPEC quotas are low, the entire inverse supply curve is simply shifted to the left, thus increasing equilibrium price. Conversely, larger quotas induce lower oil prices. It is also easy to see that oil price is equal to the marginal production cost of the last non-OPEC producer.

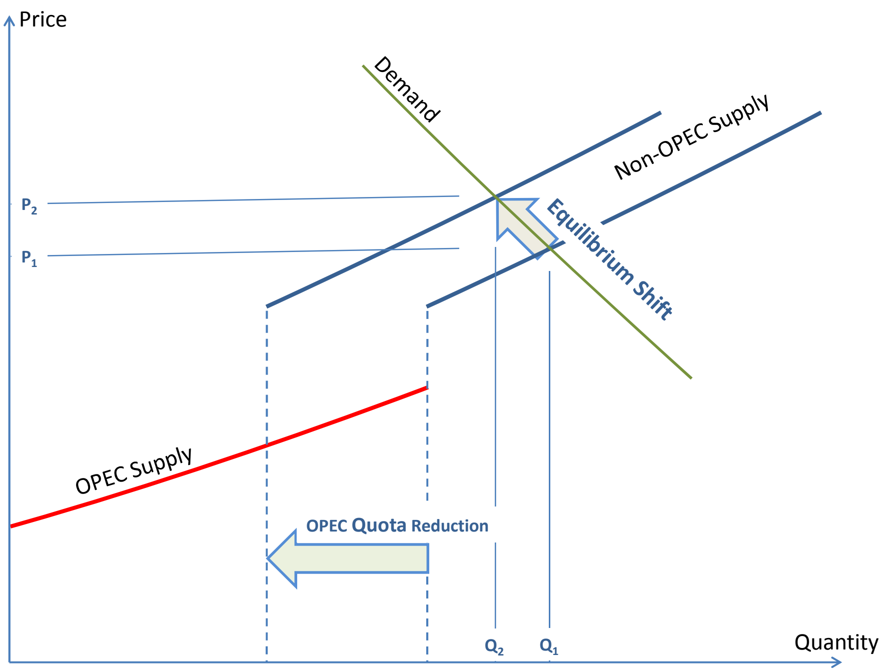

Figure 1. Impact of OPEC quotas on equilibrium

One may argue that OPEC periodically re-adjusts its quotas, after observing the reaction of the rest of the World, and in particular oil price which is highly uncertain. Therefore, the real life situation is closer to a stochastic dynamic game with closed-loop strategies. Stackelberg solutions for games having this information structure are notoriously difficult to characterize and compute on detailed numerical models.

Additional conditions that determine oil price in real life may also include:

- Accidental production reductions in OPEC and non OPEC countries due to hazards, wars, strikes, etc.

- Exercise of market power by major refiners (either for speculative purposes or due to insufficient refining capacity, in the short or long term); accidental reductions of refinery capacity, as resulting from the Hurricanes Katrina and Rita, might also have an impact on refined oil price;
- Inclusion of risk considerations by consumers, and more generally, buyers behaviors that result from an imperfect knowledge of future market conditions, resulting in the constitution of stocks to protect against short term oil supply fluctuations;
- Lack of flexibility of non-OPEC producers, leading to insufficient production capacity to satisfy demand increases (such as the recent surge in demand by Asian countries), etc.

However, all these phenomena occur at a time scale which is much shorter than the one considered in the analysis of long-term climate policies and they are not represented in these models. In spite of these limitations, it is our contention that by considering an open-loop information structure for the OPEC Stackelberg game, we are able to introduce a strategic dimension in the definition of long term oil price and therefore to take into account the possible reaction of OPEC to a worldwide climate regime resulting from international climate negotiation. More precisely, we are interested in exploring what quota strategies would be followed by OPEC in two radically contrasted situations: a Reference scenario, where the World is not concerned with climate change, and a Climate scenario, where the World agrees on a strict Climate policy.

- In the ***Reference Scenario***, we conjecture that OPEC strategy to maximize its profit will consist in reducing its quotas (compared to a global competitive equilibrium).
- In the ***Climate scenario***, the situation is less clear: one the one hand, since the imposition of a climate target will induce a worldwide decrease of oil consumption, it is tempting to say that OPEC will want to increase its quotas and thus trigger a decrease of oil prices in order to induce a rebound of global oil demand. On the other hand, one may argue that in the Climate scenario, worldwide demand for oil is already so much reduced that the residual oil consumption is fairly inelastic (i.e. destined for uses that are very difficult to substitute with other fuels); and if this is indeed the case, then OPEC should in fact *decrease* its quotas (and thus trigger an increase of oil prices) so as to take full advantage of the 'captive' residual oil demand. Our experiment will test these two alternative conjectures.

The next section describes our approach and assumptions for simulating a simplified version of the Stackelberg game just described, in each of the two alternate scenarios.

3 Exploring OPEC strategies with the TIAM model

We use the partial equilibrium global TIAM model to assess the impact of a variety of OPEC quotas on oil prices and ultimately on OPEC oil profits and on global welfare. The market imperfections listed in section 2 are ignored in order to focus on the main aspect of OPEC's behavior, namely the setting of quotas so as to maximize OPEC's net long term oil revenues. In addition, we assume that OPEC's quota strategy is set at the beginning of the planning horizon, i.e. we simulate an open loop Stackelberg equilibrium, rather than the real-life game with feedback. This simplifying assumption is in keeping with the perfect foresight property of our equilibrium model.

3.1 The TIAM model

The TIAM model was developed over a 5 year period (2004-2008) with the objective of marrying the technological detail of TIMES models with a global view of the world energy system, emissions, and climate. TIAM is a 15 region, long term (up to 2100) technology-rich model that integrates the World energy system and a climate module. It is based on the computation of a partial equilibrium on energy and emission markets, where the demands for energy services in each region are elastic to their own prices. Trade between regions is modelled for all energy forms and permits. The appendix A gives more details on the model, as well as [11, 12]. We now provide some details on the model that are of particular importance for the analysis of oil strategies.

In each region, OPEC upstream sector (including oil production and refining) is distinguished from non OPEC, so as to allow simulations of policies that are specific to OPEC. The economic and technical data on existing and future fossil resources originate from the US-DOE EIA database [20] and have been recently reviewed [17]. Fossil energy resources are modeled as step-wise supply curves in each OPEC and non-OPEC region, with specific extraction costs for each step of each category of supply. Oil resources are subdivided into several types such as conventional, oil sands/ ultra heavy oils, and oil shales. Each type is modeled via three elements: a cumulative amount of the resource in the ground (Table 1), an annual maximum extraction rate (representing good practice and technical limitation in each region), and a variable extraction cost. These three elements define a supply curve for each oil type in each region. Co-production of oil and derived natural gas is also modeled. Once extracted, oil is either sent directly to the refinery (conventional oil) or further processed (oil sands, oil shales) before refining.

Finally, TIAM features endogenous trading of 9 energy forms and 3 emission permits, as follows: coal, natural gas (gaseous and liquefied), natural gas liquids, crude oil, and four refined oil products (gasoline, heavy fuel oil, distillates, naphtha). Each traded energy form has its specific transportation cost between each pair of regions. This allows the modeler to simulate trade with some precision. The trade of CO2 permits, of permits of non-CO2 only, and of general GHG permits is also possible. If desired, one can also introduce transaction costs for trading emission permits.

Table 1. Cumulative oil resources (EJ)

	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	*WORLD*
Crude oil (ground) - Located reserves - Step 1 - Nopec	73	15	194	86	96	10	270	19	0	48	67	31	-	131	96	*1136*
Crude oil (ground) - Located reserves - Step 2 - Nopec	44	9	116	52	58	6	162	12	0	29	40	18	-	79	58	*682*
Crude oil (ground) - Located reserves - Step 3 - Nopec	29	6	78	34	38	4	108	8	0	19	27	12	-	53	38	*454*
Crude oil (ground) - Reserves growth - Step 1 - Nopec	30	7	65	38	42	7	163	8	0	20	36	18	-	168	48	*649*
Crude oil (ground) - Reserves growth - Step 2 - Nopec	18	4	39	23	25	4	98	5	0	12	22	11	-	101	29	*390*
Crude oil (ground) - Reserves growth - Step 3 - Nopec	12	3	26	15	17	3	65	3	0	8	14	7	-	67	19	*260*
Crude oil (ground) - New discovery - Step 1 - Nopec	115	14	8	34	243	5	285	7	-	28	59	21	-	-	193	*1012*
Crude oil (ground) - New discovery - Step 2 - Nopec	69	9	5	21	146	3	171	4	-	17	35	13	-	-	116	*607*
Crude oil (ground) - New discovery - Step 3 - Nopec	46	6	3	14	97	2	114	3	-	11	23	8	-	-	77	*405*
Oil sands (ultra hvy) - Located reserves - Step 1 - Nopec	2	-	987	-	0	-	160	-	-	0	-	-	-	0	0	*1150*
Oil sands (ultra hvy) - Located reserves - Step 2 - Nopec	2	-	987	-	0	-	160	-	-	0	-	-	-	0	0	*1150*
Oil sands (ultra hvy) - Located reserves - Step 3 - Nopec	1	-	493	-	0	-	80	-	-	0	-	-	-	0	0	*575*
Oil sands (ultra hvy) - Enhanced recovery - Step 1 - Nopec	0	-	-	1	0	0	-	-	-	-	0	-	-	0	1	*3*
Oil sands (ultra hvy) - Enhanced recovery - Step 2 - Nopec	0	-	-	1	0	0	-	-	-	-	0	-	-	0	1	*3*
Oil sands (ultra hvy) - Enhanced recovery - Step 3 - Nopec	0	-	-	1	0	0	-	-	-	-	0	-	-	0	0	*1*
Shale oil (ground) - Located reserves - Step 1 - Nopec	148	29	14	15	75	16	253	-	-	39	-	8	-	2418	84	*3098*
Shale oil (ground) - Located reserves - Step 2 - Nopec	148	29	14	15	75	16	253	-	-	39	-	8	-	2418	84	*3098*
Shale oil (ground) - Located reserves - Step 3 - Nopec	74	14	7	7	37	8	126	-	-	19	-	4	-	1209	42	*1549*
Crude oil (ground) - Located reserves - Step 1 - Opec	255	-	-	-	720	-	-	-	-	2100	-	23	-	-	-	*3098*
Crude oil (ground) - Located reserves - Step 2 - Opec	153	-	-	-	432	-	-	-	-	1260	-	14	-	-	-	*1859*
Crude oil (ground) - Located reserves - Step 3 - Opec	102	-	-	-	288	-	-	-	-	840	-	9	-	-	-	*1239*
Crude oil (ground) - Reserves growth - Step 1 - Opec	100	-	-	-	217	-	-	-	-	674	-	14	-	-	-	*1005*
Crude oil (ground) - Reserves growth - Step 2 - Opec	60	-	-	-	130	-	-	-	-	404	-	8	-	-	-	*603*
Crude oil (ground) - Reserves growth - Step 3 - Opec	40	-	-	-	87	-	-	-	-	270	-	5	-	-	-	*402*
Crude oil (ground) - New discovery - Step 1 - Opec	153	-	-	-	56	-	-	-	-	571	-	18	-	-	-	*797*
Crude oil (ground) - New discovery - Step 2 - Opec	92	-	-	-	34	-	-	-	-	342	-	11	-	-	-	*478*
Crude oil (ground) - New discovery - Step 3 - Opec	61	-	-	-	22	-	-	-	-	228	-	7	-	-	-	*319*
Oil sands (ultra hvy) - Located reserves - Step 1 - Opec	96	-	-	-	-	-	-	-	-	-	-	1	-	-	-	*97*
Oil sands (ultra hvy) - Located reserves - Step 2 - Opec	96	-	-	-	-	-	-	-	-	-	-	1	-	-	-	*97*
Oil sands (ultra hvy) - Located reserves - Step 3 - Opec	48	-	-	-	-	-	-	-	-	-	-	0	-	-	-	*48*
Oil sands (ultra hvy) - Enhanced recovery - Step 1 - Opec	-	-	-	-	644	-	-	-	-	-	-	-	-	-	-	*644*
Oil sands (ultra hvy) - Enhanced recovery - Step 2 - Opec	-	-	-	-	644	-	-	-	-	-	-	-	-	-	-	*644*
Oil sands (ultra hvy) - Enhanced recovery - Step 3 - Opec	-	-	-	-	322	-	-	-	-	-	-	-	-	-	-	*322*
Shale oil (ground) - Located reserves - Step 1 - Opec	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Shale oil (ground) - Located reserves - Step 2 - Opec	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Shale oil (ground) - Located reserves - Step 3 - Opec	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

3.2 Simulating OPEC strategies with TIAM

We examine two series of OPEC strategies: one for the *Reference scenario*, the other for the *Climate scenario*.

- ***Reference Scenario runs***: We first run TIAM with no quotas, i.e. we compute a *competitive equilibrium* as if OPEC were not a cartel (run noted RE for Reference). In this run, the only constraints on oil production are technical constraints that translate the good practices of oil extraction. We then conduct a series of runs (named RE-X), each of which imposes a fixed set of production reductions to X% of the OPEC oil production levels observed in the RE run, where X varies from -60% to +40%. Note that all these runs with the exception of RE represent a departure from the competitive equilibrium.
- ***Climate Scenario runs***: Similarly, we first conduct a run with no quotas (competitive equilibrium) but including a constraint on Radiative Forcing equal to 3.5 W/m^2 in 2100 (run noted CL). This is a severe constraint that is expected to contain the increase in average global temperature within 2^oC through the 21^{st} century[1]. We then conduct a series of runs with oil production quotas, named CLX, each of which imposes a quota reduction or increase equal to X% of OPEC's oil production in the CL run, X varying from -70% to +30% The smaller range chosen for these runs is sufficient to detect the optimal[2] strategy. Again here, all these runs, with the exception of run CL, all depart from the competitive equilibrium.

For each run, we obtain directly from the model's results the following quantities:

- OPEC's production levels and production costs;
- OPEC's oil exports;
- Oil prices;
- Net Global Surplus for the energy system.

From these quantities, we construct two major indicators:

- OPEC's oil profits = oil revenues - production costs
- Global loss of welfare relative to the competitive equilibrium defined as the difference between the global surplus in the run without quotas and the global surplus in the run with quotas.

In sections 4 (Reference case) and 5 (Climate case), we examine the various oil production strategies by OPEC in each of the two scenarios. In section 6, we provide additional comparison elements of the optimal strategies in the two scenarios.

4 Results and discussion for the REFERENCE scenario

In this section, we examine the various oil production strategies by OPEC in the reference case, focusing on OPEC's profits and on global welfare losses. We then discuss the resulting optimal production strategy from OPEC's viewpoint and look at the actions of the followers, i.e. the oil production by non-OPEC regions as well as the World oil consumption for this optimal OPEC strategy.

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[1] We use a value of 3^oC for climate sensitivity parameter C_s. For higher values of C_s and the same constraint on Forcing, the global temperature increase would be larger than 2^oC.

[2] Throughout this article, we use the phrase *optimal strategy* in a loose sense. It is clear that our exploration of OPEC quota strategies is not exhaustive. For instance, there are strategies where OPEC might initially increase its quotas and later decrease them, etc. Therefore, our exploration of quotas is only partial. It should however provide insights into the general direction that OPEC would take in setting its quotas.

4.1 *OPEC's optimal quota strategies*

4.1.1 OPEC's oil profits

Figure 2 shows the net present value (NPV) of OPEC's oil profits for each of the 8 tested quota strategies. The highest profit is reached when quotas are 80% of the levels in the competitive equilibrium (RE-20). OPEC obtains a net extra gain of 990 B$ from following the optimal strategy rather than the competitive equilibrium RE. Note however that these results do not take into account the value of residual oil at the end of the horizon.

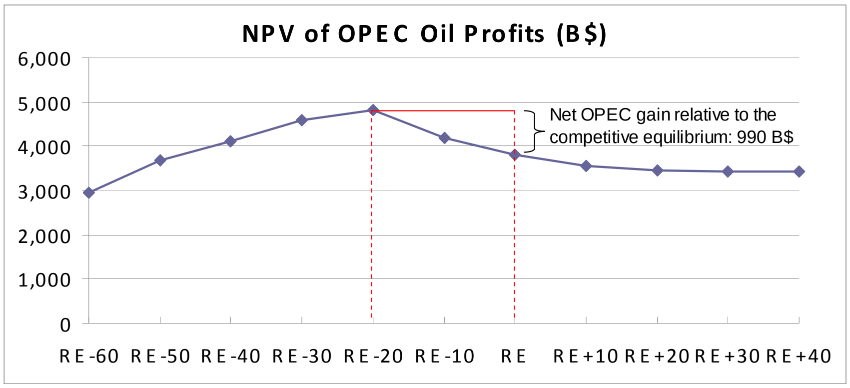

Figure 2. NPV of OPEC's oil profits for the various quota strategies (B$, Reference Scenario)

In all cases, the profits tend to drop toward the end of the century (Figure 3), indicating that OPEC oil is peaking (note however that these results do not take into account the value of residual oil at the end of the horizon). While profits remain high throughout the horizon for policies with large quotas, they tend to drop sharply when quotas are decreased (an expected result), becoming negative for the most severe ones, indicating that OPEC becomes a net importer of oil in those two strategies (see subsection 4.1.2). Finally, OPEC's net oil profits are much more sensitive to quotas that OPEC's production levels (Figure 5), because OPEC must first satisfy its own oil demand, thus incurring an essentially fixed cost.

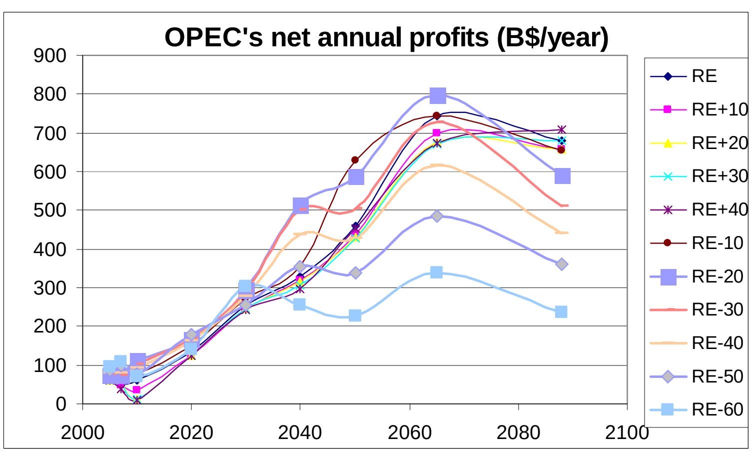

Figure 3. OPEC's net annual profits (B$/yr)

4.1.2 OPEC's oil production and exports

Exports (Figure 4) do *not* closely follow the same shape as the production levels (Figure 5), because OPEC countries must also satisfy their own rising demand for oil. The dip in exports around mid-century is due to a stabilization of global oil consumption (see section 4.2.1.). The decline of exports at the end of the century in all strategies indicates that OPEC oil is indeed peaking, and oil production starts declining. In the most severe quota strategies, OPEC even becomes a net oil importer toward the end of the century.

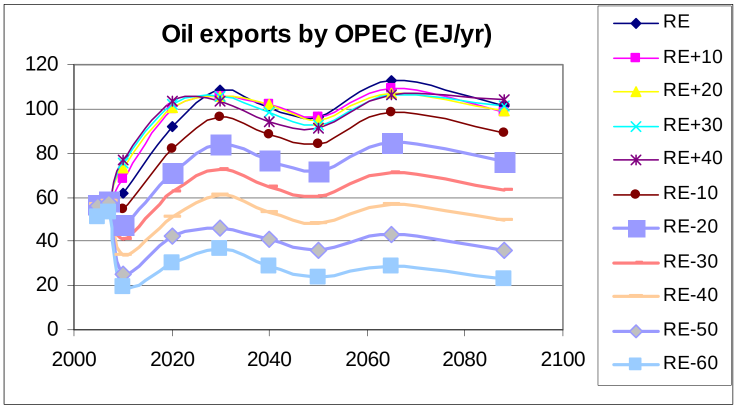

Figure 4. Annual Oil Exports by OPEC (EJ/yr)

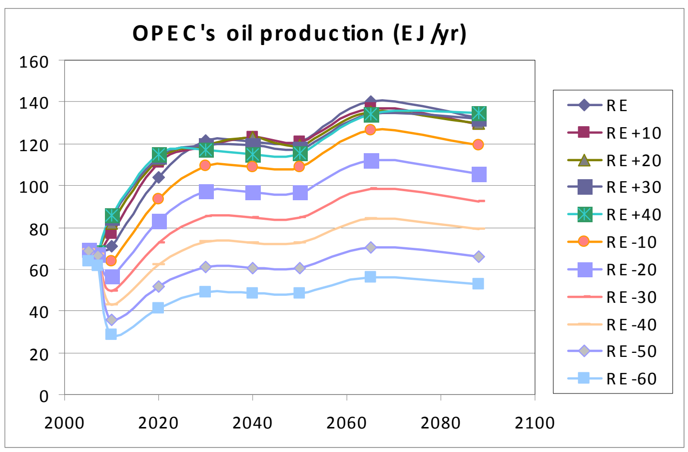

Figure 5. Annual oil production by OPEC (EJ/yr)

4.1.3 Oil prices

Oil prices (Figure 6) are lowest and almost identical for the four strategies that maintain quotas at least equal to the equilibrium quantities (RE+10 to RE+40). This suggests that "flooding" the World with oil has very little impact on World demand, as will be confirmed in section 4.2.1. However, reducing quotas has a strong impact on prices: the most severe quota policy entails prices that are between 150% and 200% of the lowest prices in the mid-term. Toward the end of the horizon, prices tend to equalize somewhat, indicating that he supply curve of the non-OPEC countries is reaching its most expensive layers, irrespective of the OPEC production level.

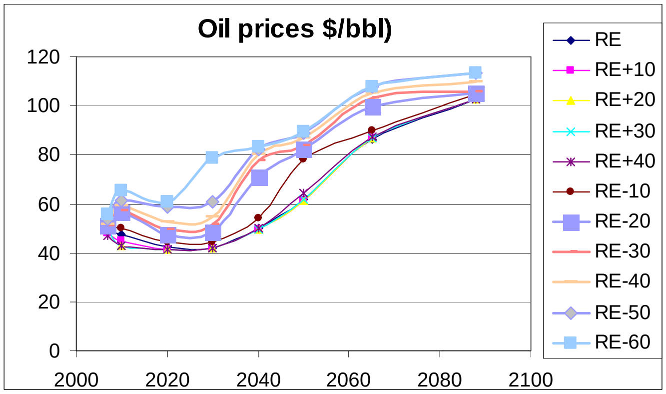

Figure 6. Oil prices ($/bbl)

4.2 Reaction by the Followers

4.2.1 Oil production by non-OPEC and world oil consumption

A quasi-stabilization of World oil consumption is observed after 2050 (Figure 7). This is the result of a slight decline in OPEC production and a slight increase in non OPEC production. Moreover, global oil consumption trajectories significantly differ from one another only from 2030 to 2050. Therefore, OPEC's strict quotas do have an impact on oil consumption, at least around mid-century. Earlier, the technologies for reducing oil demand are not yet fully ripe, and furthermore oil prices are not high enough to induce strong substitution of oil by other fuels, whereas after 2050, oil prices are sufficiently high in all strategies as to induce roughly the same technological choices irrespective of oil quotas. In summary, OPEC's strict quotas have the effect of simply *advancing* the switch toward alternative fuels that occurs in all cases.

The non-OPEC'oil production fills in the gap between the global oil consumption and the OPEC production (Figure 8). In the competitive equilibrium, it varies between 27% and 48% of the World production. It reaches more than half of the World consumption in all cases where OPEC reduces its production, but also in the intermediate periods (2040-2050) of the cases where OPEC increases a lot its own production.

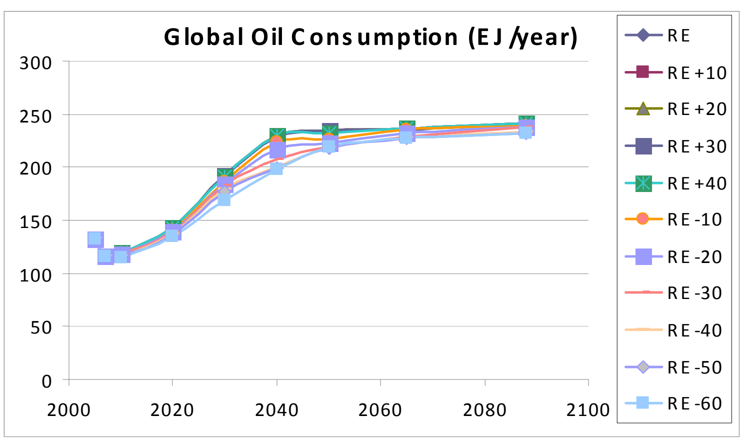

Figure 7. Global oil consumption (EJ/yr)

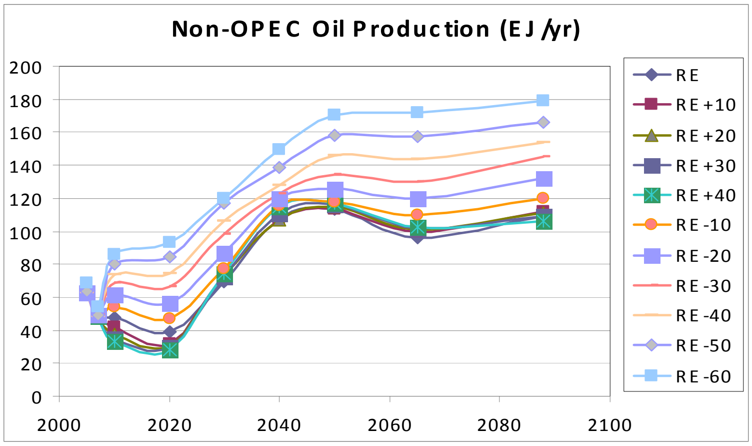

Figure 8. Oil production by non-OPEC countries (EJ/year)

4.2.2 Emissions and technological responses

First, the emission trajectories are not affected by the OPEC's quota strategies. In other words, the climate is not affected by the energy and technology changes resulting from OPEC strategies.

The main sector using oil products is of course the *Transportation sector*. One of the main impacts of the reduction of OPEC's quotas in the expected penetration of alternative fuels, being natural gas in the intermediate horizon (2010-2040) followed by alcohols in the longer term. It is however interesting to note the return of diesel fuel in the longer term, after a decrease in the intermediate horizon, corresponding to the availability of more efficient diesel vehicles. In other words, it is more cost-efficient to delay the consumption of diesel in the longer term.

The second sector more affected by the reduction of OPEC's quotas is *industry*, where the strict quota strategies make coal much more attractive (and, to a lesser extent, biomass, especially to produce process heat in industry). The dynamics behind this change is not only the decrease of the available oil, but *the strong increase of gas demand for upstream activities*, i.e. for the extraction of oil sands in non-OPEC regions in the longer term (Figure 9) when OPEC reduces it own production, as observed in section 4.2.1.

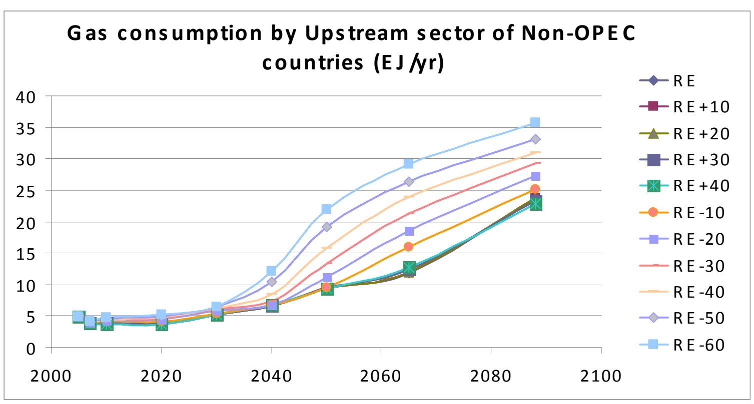

Figure 9. Gas consumption by upstream sector of Non-OPEC countries

The *residential and commercial sectors* are affected only in the longer term and to a lesser extent, when electricity substitutes both oil products and natural gas mainly to satisfy the needs for space heating.

The *electricity sector* is not affected by the OPEC strategies in any significant manner.

Finally, in *all end-use sectors*, the larger quotas by OPEC countries have a much less visible effect than the strict quota strategies. As already explained, "flooding" the World with oil has little impact on oil demand. Oil products slightly reduce the penetration of LPG, natural gas and alcohols in transport, of coal in industry and of gas in residential and commercial sectors, but the susbtitution is far less important than in the case of reduced production by the OPEC countries.

4.3 Global loss of surplus (welfare)

The optimal OPEC strategy (RE-20) entails a global loss of surplus of 698 B$ (Figure 10) relative to the competitive strategy (which by definition has the highest global surplus). Since OPEC extra profits are 990 B$, this means that non-OPEC countries (the Followers) incur a net loss of 1690 B$. This is equivalent to a per capita annuity of around $10 for each Non-OPEC inhabitant of the planet, for the rest of the 21st century, a not insignificant amount. It is thus apparent that OPEC's interests are somewhat opposed to those of the global citizen. Note that the loss increases much more sharply when the quotas are reduced than when they are increased. This is expected, as decreasing quotas provokes scarcity and forces non-OPEC producers to produce oil at high marginal cost, whereas increasing OPEC production above the equilibrium quantity has almost no impact on global oil consumption, and only entails some loss of economic efficiency.

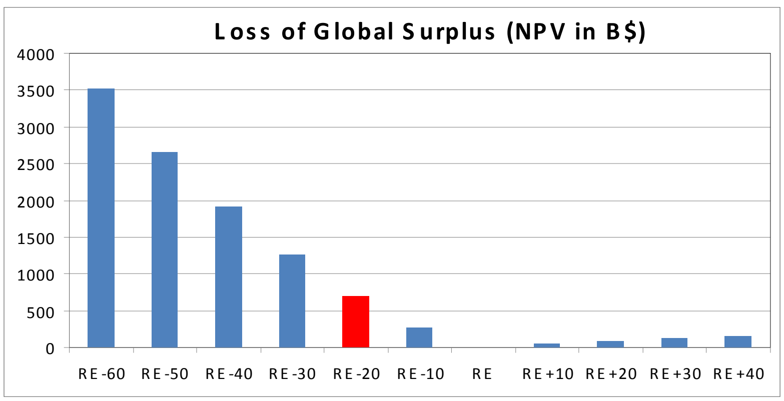

Figure 10. Loss of Global Surplus (NPV in B$)

5 Strategies for the Climate Case

In this section, our main objective is still to analyze the optimal quota policy by OPEC, but considering a World climate agreement corresponding to a limit of the radiative forcing equal to 3.5 W/m^2 in 2100. Of course, we cannot ignore the fact that the Climate target of 3.5 W/m^2 has a profound impact on the global energy system, including a sharp decrease in global oil consumption, as will be seen further down. However, for practical reason, this section presents the same results as the previous section, emphasizing only the most important ones.

5.1 OPEC's Optimal Quota Strategy

5.1.1 OPEC's Profits

The highest OPEC's oil profit is reached when quotas are reduced 20% relative to the competitive equilibrium (Figure 11), and the –70% strategy comes a close second. The optimal quotas in Reference scenario were also obtained for a 20% reduction of equilibrium quantities, but of course, these optimal levels are different in absolute terms from those in the Reference scenario. OPEC obtains a net gain of about 1060 B$ from following the optimal strategy, relative to a no quota strategy.

The various quota strategies produce profits that are close together initially, but then diverge markedly after 2040 (Figure 12). We remind that these results do not take into account the value of residual oil at the end of the horizon.

Remark: The drop of profit in the CL+20 and CL+30 strategies is due to the combination of three factors: first, oil prices are slightly lower (Figure 15); next, when forcing its oil production to increase, OPEC itself incurs increasingly larger marginal production costs (its supply curve is not flat), thus decreasing its unit profit margin, and finally, these two factors are not counterbalanced by increased oil exports, which are very slight, in part due to the technical constraints on annual oil extraction.

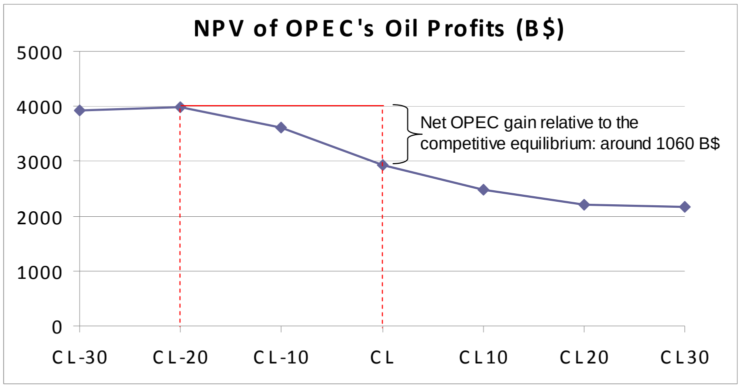

Figure 11: NPV of OPEC's oil profits for the various quota strategies (B$, Climate Scenario)

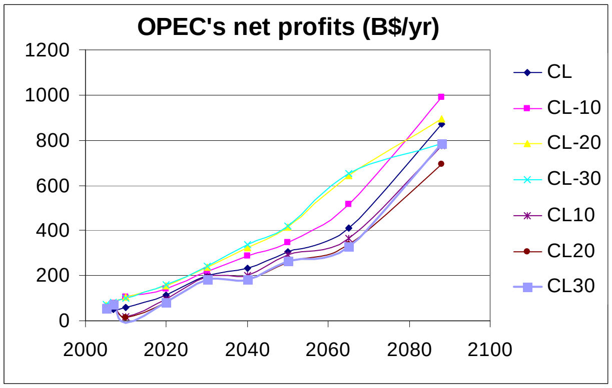

Figure 12. OPEC's Oil Profits (B$/yr)

5.1.2 OPEC's oil production and exports: no rebound

OPEC's oil production and export profiles (Figures 13 and 14) result in an important finding: the loose quota policies do not really induce much extra exports. This finding contradicts a conjecture according to which OPEC could provoke a rebound of oil demand (Figure 16) by freeing its production. The lack of rebound is explained by two facts: a) loose quotas do not succeed in decreasing oil prices sufficiently (Figure 15) to provoke a significant rebound effect in the ROW, and b) the severe climate target is more important in determining oil demand than OPEC's policies.

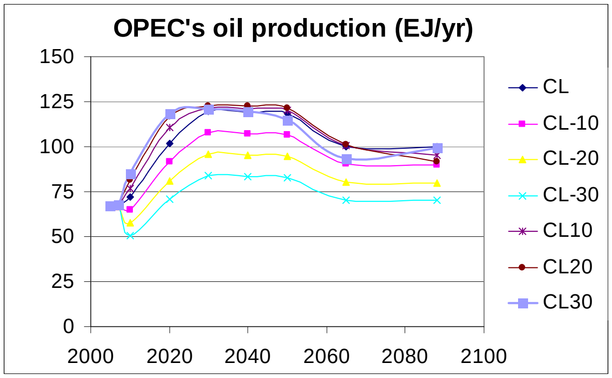

Figure 13. Annual oil production by OPEC (EJ/yr)

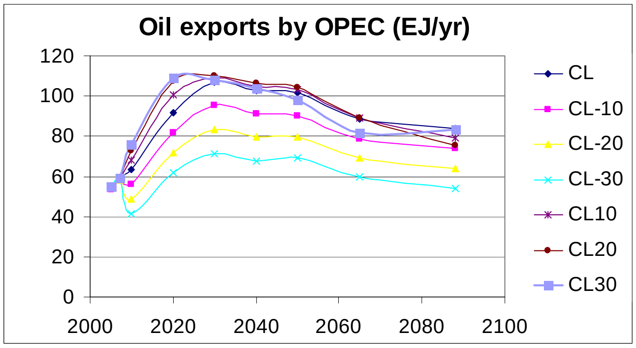

Figure 14. OPEC's Oil Exports (EJ/yr)

5.1.3 Oil Prices

Oil prices are quite insensitive to an increase of OPEC's production, mainly because World oil demand does not increase much (no significant rebound effect: the climate target, making oil a less desirable commodity, is more powerful) and thus non-OPEC producers produce less oil, at a correspondingly lower marginal cost.

In contrast, strict quotas do have a significant impact on oil prices: the most severe quota policy (CL-30) entails prices that are between 130% and 160% of the lowest prices from 2030 to 2080. Note that in contrast with the Reference scenario, prices do not tend to equalize toward the end of the horizon, because oil is not peaking in the Climate scenario, whereas it was in Reference (see section 5.2).

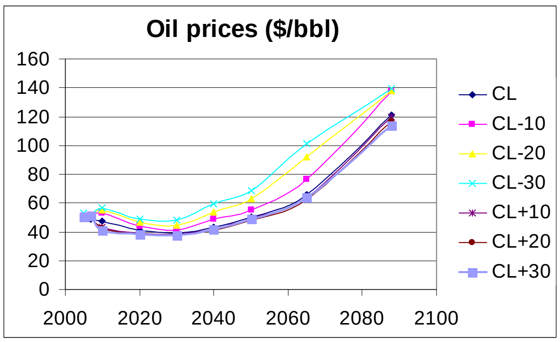

Figure 15. Oil prices ($/GJ)

5.2 *Responses by the Followers*

5.2.1 Oil production by non-OPEC and World oil consumption

Global oil consumption and non-OPEC oil production both peak in 2040 (Figure 16 and 17), not because of resource exhaustion, but because of the Climate target. By contrast, recall that global oil demand did not decrease in the Base scenario, and the peak in non OPEC production occurs 20 years earlier than in the Base Scenario.

Until 2030, the world oil demand is little affected by the climate target and by the OPEC quotas, in part because of the rigidity of the existing technology system, and in part because it is optimal to wait until oil prices are high enough and alternative technology are cheap enough before decreasing oil demand. As a result, the non-OPEC producers more or less compensate for the lack of OPEC oil induced by quotas, by increasing their production (Figure 16). However, after 2030, this is no longer the case, as alternate vehicles become increasingly competitive and as the climate constraint exerts a strong pressure to decrease oil use. Therefore global oil consumption decreases as quotas decrease, the decrease reaching 20% in 2040 for the CL-30 quota strategy.

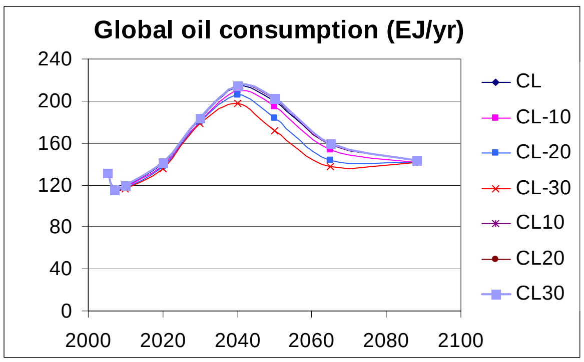

Figure 16. Global Oil Consumption (EJ/yr)

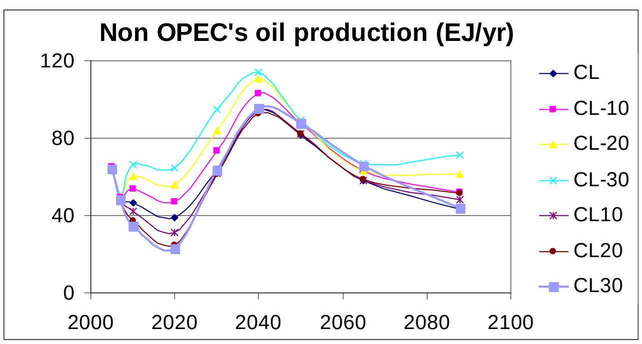

Figure 17. Non OPEC Oil Production

5.2.2 Emissions and technological responses

The climate constraint requires a decrease of the CO2 emissions from 35.6 GtC in the Reference case at the end of the horizon to 3.6 GtC in the Climate scenario (Figure 18). The most important options to abate the CO2 emissions are: the sequestration of CO2 by forests, a large substitution of coal by biomass and gas in the intermediate horizon in industry (mainly for the processes and the production of steam for all subsectors), followed by the substitution of all fossil fuels by electricity in industry, residential and commercial sectors (mainly heating in the latter) in the longer term, while the power sector is characterized by the progressive replacement of conventional coal power plants by advanced gas and coal power plants with sequestration, by hydroelectricity as well as renewable in the longer term. More efficiency technologies also largely penetrate, especially the electric ones (for example, lighting). The decrease of the end-use demands for energy services, resulting from the increase of energy prices, reaches up to 15% in the residential and commercial sectors (such as the demands for office equipment), up to 14% in the industrial sector, 5% in the road transport, In the road transport sector, alcohols substitute conventional gasoline and diesel.

The impact of OPEC strategies can be neglected on the climate (temperature, forcing) while the loose quotas result in earlier reductions of emissions, followed however by a slightly higher peak of emissions and again by lower emissions at the long term compared to the strict quotas (Figure 19). In other words, the strict quotas contribute to relatively smoothing the emission trajectory.

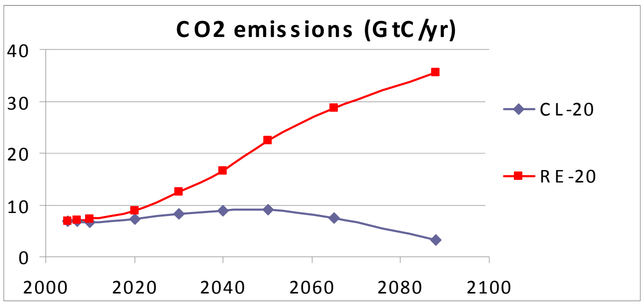

Figure 18. CO2 emissions in the two optimal scenarios

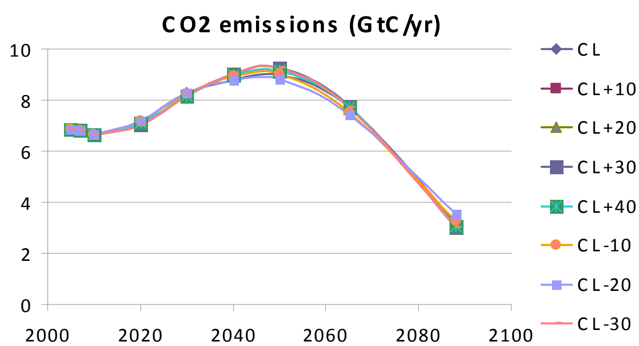

Figure 19. CO2 emissions in the different OPEC's strategies under climate regiome

The main impacts of the OPEC's quota strategies on the technology decisions under the climate regime follow. First, given the decrease of oil consumption after 2040, the contribution of non conventional oil extracted in Non-OPEC countries is much smaller, so that the increase of the gas demand by *upstream*, although visible, is not as high as in the cases without climate constraint. The OPEC strategies still affect the fuels consumed by the *transportation* sector: the strict quotas reinforce the substitution of oil products by natural gas in the first part of the horizon (in a moderate manner), and by alcohols after 2040. In *residential and commercial sectors*, strict OPEC's quotas help substituting the consumption of oil products by electricity for space heating. However, *industry*, both in terms of energy and feedstock consumption, appears to be insensitive to OPEC strategies. *Electricity production* remains also almost insensitive to the OPEC strategies, the only visible impact being the earlier replacement of conventional coal power plants by plants with capture under loose quotas, corresponding to an earlier sequestration of carbon in geological sinks, while sequestration by forest remain unchanged (its low price makes this option always used at it maximal potential).

To summarize, the strict quotas by OPEC tend to reinforce the technology and energy change induced by the climate regime, but without changing drastically any decision.

5.3 Global Loss of Surplus

The optimal OPEC strategy (CL-20) entails a global surplus loss of 539 B$ (Figure 20) relative to the competitive strategy. The global welfare loss due to OPEC strategy is thus 30% less than in the reference case (without climate constraint). Since OPEC's extra profits are 1062 B$, this means that non-OPEC countries (the Followers) incur a net welfare loss of 1601 B$. This is equivalent to a per capita annuity of around $9 for each Non-OPEC inhabitant of the planet, for the rest of the 21st century.

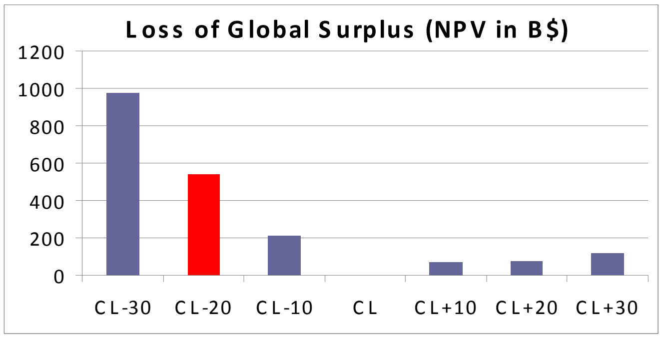

Figure 20. Net Loss of Global Surplus (B$)

6 Comparison of the optimal OPEC strategies with and without a climate regime

This section first compares the OPEC's optimal strategies for the two series of scenarios, Reference and Climate, and then briefly analyses the impacts of OPEC strategies on emisions and energy. We recall that OPEC's optimal quotas were found to be at 80% of the corresponding competitive equilibrium values in both the Reference and the Climate scenarios. However, the absolute values of the equilibrium oil production levels are of course different in the two contrasted scenarios.

6.1 Oil exports and global consumption

The two export profiles (Figure 21) stay rather close together, with only a slight decrease in the Climate scenario, whereas world consumption decreases dramatically. This is no surprise, since a decrease in oil consumption mainly (negatively) affects the more expensive producers, which are in non-OPEC countries. An additional factor explaining the relatively small decrease of OPEC's exports despite the decrease of the world consumption may be that OPEC'oil is conventional, and its extraction emits less GHG's that non conventional oil, which is produced exclusively in non-OPEC countries. Hence the preferred reduction of the production of the latter.

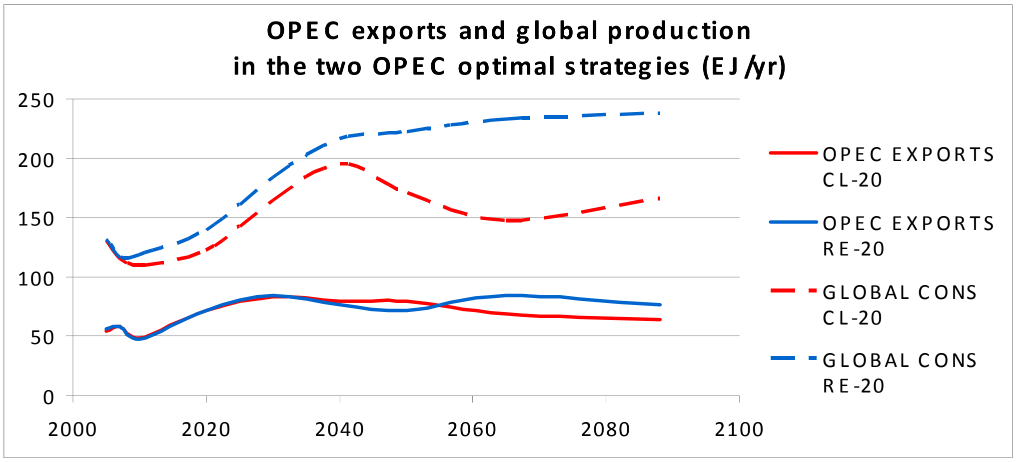

Figure 21. OPEC exports and global consumption in the the two optimal OPEC strategies

6.2 Oil profits

The dynamic profiles of the annual profits differs between the two cases (Figure 22). In fact, the sharp decrease in profits shown in the last portion of the century for the Reference scenario (already discussed above) is more than compensated by the larger profits in the earlier years (aided by a lower discounting of the early profits). The OPEC profits are thus significantly higher in the Reference case than in the Climate NPV, indicating a probable preference of OPEC for a situation without any climate regime.

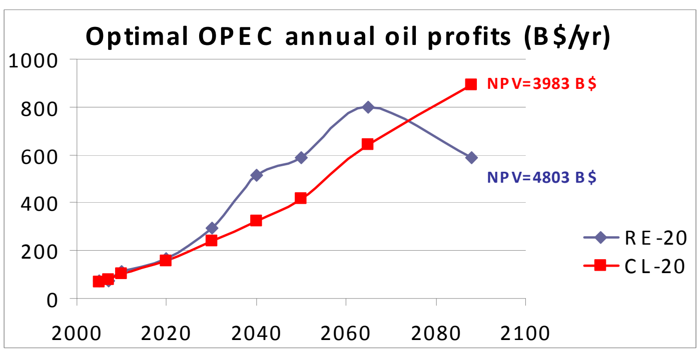

Figure 22. OPEC optimal annual profits for the two scenarios

6.3 Climate regime

It is very interesting to observe the extent to which OPEC strategies might influence the global cost of attaining the climate target. A comparison of the global cost due to the climate constraint with and without OPEC quotas (Table 2) shows that the optimal quota strategy of OPEC *decreases* the global cost of climate mitigation by 159 B$ or about 1.4%, which is not very significant. We may conclude that OPEC's quotas have a minor influence on the conduct of a global climate strategy

Table 2. Absolute and relative global costs of the various combinations of scenarios and strategies

(All costs NPV in B$)	**A = C - B** Cost of Climate constraint	**B** Absolute cost of Reference scenario	**C** Absolute cost of Climate scenario
Without OPEC quotas	16661	228599	245260

With optimal OPEC quotas	16502	229297	245800
Difference (Without quota – With quotas)	159	698	539

6.4 Oil prices

The climate constraint makes oil a less desirable commodity, hence the lower price in the Climate case compared to the Reference case until the second part of the time horizon (Figure 23) where the increase of the oil price in the Climate case reflects the high price of carbon at the end of the century[3].

The OPEC strategies have an important impact of the oil prices, the latter increasing up to 40% in the optimal OPEC strategies compared to the competitive strategy.

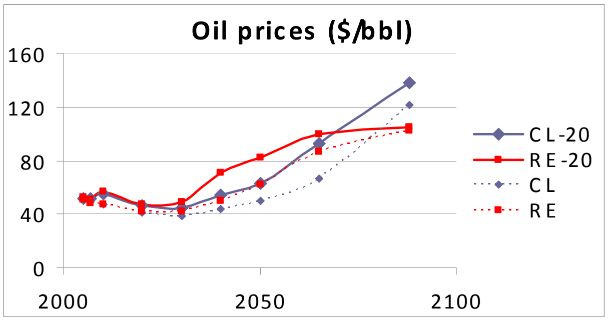

Figure 23. Oil prices in the two optimal scenarios

7 Conclusions

The main lessons learned from the experiments described in this article are as follows:

Although OPEC's quota strategies have a strong impact on oil prices in the Reference case and the Climate scenario, OPEC's market power remains moderate, in the sense that the impact of OPEC's quotas on global welfare stays moderate. Of course, the gains obtained by OPEC when restricting its quotas are directly translated in a loss for the non-OPEC countries, considered as followers in such an approach. As expected, the loss of global welfare increases much more sharply when the quotas are reduced than when they are increased: decreasing quotas provokes scarcity and forces non-OPEC producers to produce oil at high marginal cost, whereas increasing OPEC production above the equilibrium quantity has almost no impact on global oil consumption, and only entails some loss of economic efficiency.

More specifically, OPEC would derive no advantage in flooding the oil market in the Climate scenario, since its own net revenues would decrease in such an event. In other words, the severe climate target is more important in determining oil demand than OPEC's policies, and thus decreasing oil prices does not induce a sufficient demand rebound to overcome the lower price. Thus, he model has revealed that the implicit price elasticity of oil demand is less than 1. In addition, the impact of OPEC strategies on the emissions and on the climate indicators (temperature, forcing) can be neglected with or without a climate constraint. However, the cost of attaining the climate target is somewhat lowered when OPEC adopts its

[3] The price of crude oil reported in this paper includes the carbon charge for upstream GHG emissions, i.e. emissions that occur at the extraction and production stages. Therefore, oil price will, *ceteris paribus*, be higher when a) carbon price is higher, and/or b) upstream emissions are higher (e.g. when oil comes from oil sands)

optimal quota strategy, what is due to the fact that the welfare loss resulting from OPEC's quota strategies happens to be larger in the Reference scenario than in the Climate scenario.

OPEC's exports are relatively insensitive to whether or not the world adopts a strict climate policy (the oil production is reduced in non-OPEC countries in the climate scenario), but OPEC's profits are lower in the Climate scenario. Thus, based on oil profits alone, OPEC may be reluctant to engage in a strict global emission reduction agreement. However, other considerations beside oil profits would come into play.

To summarize, the climate target and the OPEC's quotas could be considered as a win-win solution at the global level: the climate target reduces the negative impact of the OPEC strategy on the loss of welfare with respect to the competitive situation, and the latter slightly reduces the cost of attaining the climate target. However, both OPEC strategy and climate strategy are contrary to the respective interests of non-OPEC and OPEC countries taken independently: the OPEC's quotas induce a loss of welfare for the non-OPEC countries comparatively to the competitive situation, and OPEC's profits are indeed (negatively) affected by the adoption of a global climate target.

OPEC's quotas result in a different distribution of fuel consumption between sectors in the reference scenario, mainly motivated by the increased gas demand for the extraction and treatment of non-conventional oil by Non-OPEC countries to compensate the OPEC's decrease. In the climate scenario, OPEC quotas tend to reinforce the oil substitution by natural gas, alcohols or electricity observed under the climate regime in transport and buildings, while industry and power plants are almost insensitive to the OPEC strategies. Impacts of OPEC's quotas on energy and technology decisions are clearly more visible in the reference scenario than in the climate scenario.

Future work could consist in providing more degrees of freedom in the search for optimal OPEC 's quota strategies. Instead of a single parameter search used in this research, one could investigate more flexible strategies that allow time-dependent quotas, what would require to overcome the computational burden.

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Appendix A: The TIMES Integrated Assessment Model (TIAM)

1. Introduction

TIAM (TIMES Integrated Assessment Model) is a detailed, technology-rich global TIMES model. It is a multi-region partial equilibrium model of the energy systems of 15 regions covering the entire World. The 15 regional models are: Africa, Australia-New Zealand, Canada, Central and South America, China, Eastern Europe, Former Soviet Union, India, Japan, Mexico, Middle-East, Other Developing Asia, South Korea, United States, and Western Europe. In addition, the upstream and energy trade sectors in each country are split into OPEC/Non-OPEC. The regional modules are linked by trade variables of the main energy forms (coal, oil, gas) and of emission permits. Thus, impacts on trade (terms of trade) of environmental policies are taken into. TIAM's planning horizon extends from 2000 to 2100, divided into 7 periods of varying lengths, suitably chosen.

TIAM is a global instance of the TIMES model generator (full documentation and applications in www.etsap.org/documentation.asp), where a bottom-up, detailed technological representation of each economic sector is combined with key linkages to the macroeconomy [13, 14]. TIMES has evolved from its MARKAL forebear and has benefited from many improvements sponsored by ETSAP over the last 8 years.

In TIMES, an intertemporal dynamic partial equilibrium on energy markets is computed, where demands for energy services are exogenously specified (only in the reference case), and are sensitive to price changes via a set of own-price elasticities at each period. The equilibrium is driven by the maximization (via linear programming) of the total surplus (sum of producers and suppliers surpluses) which acts as a proxy for welfare in each region of the model. Although TIMES does not encompass all macroeconomic variables beyond the energy sector, accounting for price elasticity of demands captures a major element of feedback effects between the energy system and the economy. The maximization is subject to many constraints, such as: supply bounds (in the form of supply curves) for the primary resources, technical constraints governing the creation, operation, and abandonment of each technology, balance constraints for all energy forms and emissions, timing of investment payments and other cash flows, and the satisfaction of a set of demands for energy services in all sectors of the economy.

2. Demands

The construction of the base case demands for energy services is done via the global General Equilibrium model GEM-E3 (http://www.gem-e3.net/), which provides a set of coherent *drivers* for each region and for the World as a whole, such as population, households, GDP, sectors outputs, and technical progress. These drivers are then transformed into growth rates for each of the 42 demands for energy services (Table A1), via the generic relationship:

$$demand\_rate = driver\_rate \times decoupling\_factor\,.$$

The decoupling factors account for phenomena such as saturation (factor is then less than 1) and suppressed markets (factor is then larger than 1), and are in part empirically based. Most demands have economic growth as their driver. Note also that the demands of TIAM are user-specified only for the reference scenario, and are subject to endogenous changes in every alternate scenario, in response to endogenously changing prices. Elasticities of demands to their own price range from 0 to -0.6, with a majority in the range -0.2 to -0.3.

Table A1. Energy service demands and their driver

DEMAND	DRIVER
Transportation	**All regions**
Automobile travel	GDP/capita
Bus travel	POP
2 & 3 wheelers	POP

DEMAND	DRIVER	
Rail passenger travel	POP	
Domestic aviation travel	GDP	
International Aviation travel	GDP	
Trucks	GDP	
Fret rail	GDP	
Domestic Navigation	GDP	
Bunkers	GDP	
Residential	**All regions after 2050 + Non-OECD before 2050**	**OECD regions before 2050**
Space heating	HOU	HOU
Space Cooling	HOU	GDPP
Water Heating	POP	POP
Lighting	GDPP	GDPP
Cooking	POP	POP
Refrigeration and Freezing	HOU	GDPP
Washers	HOU	GDPP
Dryers	HOU	GDPP
Dish washers	HOU	GDPP
Other appliances	GDPP	GDPP
Other	HOU	GDPP
Commercial	**All regions**	
Space heating	SPROD-Services	
Space Cooling	SPROD-Services	
Water Heating	SPROD-Services	
Lighting	SPROD-Services	
Cooking	SPROD-Services	
Refrigeration and Freezing	SPROD-Services	
Other electric demands	SPROD-Services	
Other	SPROD-Services	
Agriculture	SPROD-Agriculture	
Industry	**All regions**	
Iron and steel	SPROD-I	
Non ferrous metals	SPROD-I	
Chemicals	SPROD-I	
Pulp and paper	SPROD-O	
Non metal minerals	SPROD-O	
Other industries	SPROD-O	

HOU: households GDPP: GDP per capita
POP: population SPROD-X: production of sector X related to GDP
GDP: gross domestic product

3. Structure of the model

The model comprises several thousand technologies in all sectors of the energy system (Figure A1). A technology may represent any process that produces, transforms, conveys, and/or consumes energy and/or emissions (and some materials). It is characterized by several technical and economic parameters and by emission coefficients for the three main GHG's: CO_2, CH_4, and N_2O. The model constructs a coherent image of the future energy system by choosing a mix of technologies to invest in and operate at each future period, with the objective of maximizing total surplus, while respecting the many constraints of the model. A complete description of TIAM's technological database is not possible within the limits of an article, but we wish to mention some options for GHG emission reductions available in the model: first, emission reductions may be done via the numerous fuel and technology switching options that are available in each sector, and via specific CH_4 and N_2O abatement options[4] (e.g. suppression and/or combustion of fugitive methane from landfills, thermal destruction of N_2O in the adipic acid industry, etc.). Also, CO_2 emissions may in some cases be captured and stored (CCS options) before their release into the atmosphere (e.g. CO_2 capture from the flue gas of fossil fueled power plants, from hydrogen production processes, and from oil extraction processes; storage in depleted oil fields, deep saline aquifers, deep oceans, etc.). Finally, atmospheric CO_2 may be partly absorbed and fixed by biological sinks such as forests; the model has six options for forestation and avoided deforestation, as described in [24] and adopted by the EMF-22 group. Note also that methane emissions from the agriculture sector are fully accounted for, even if no abatement options are considered.

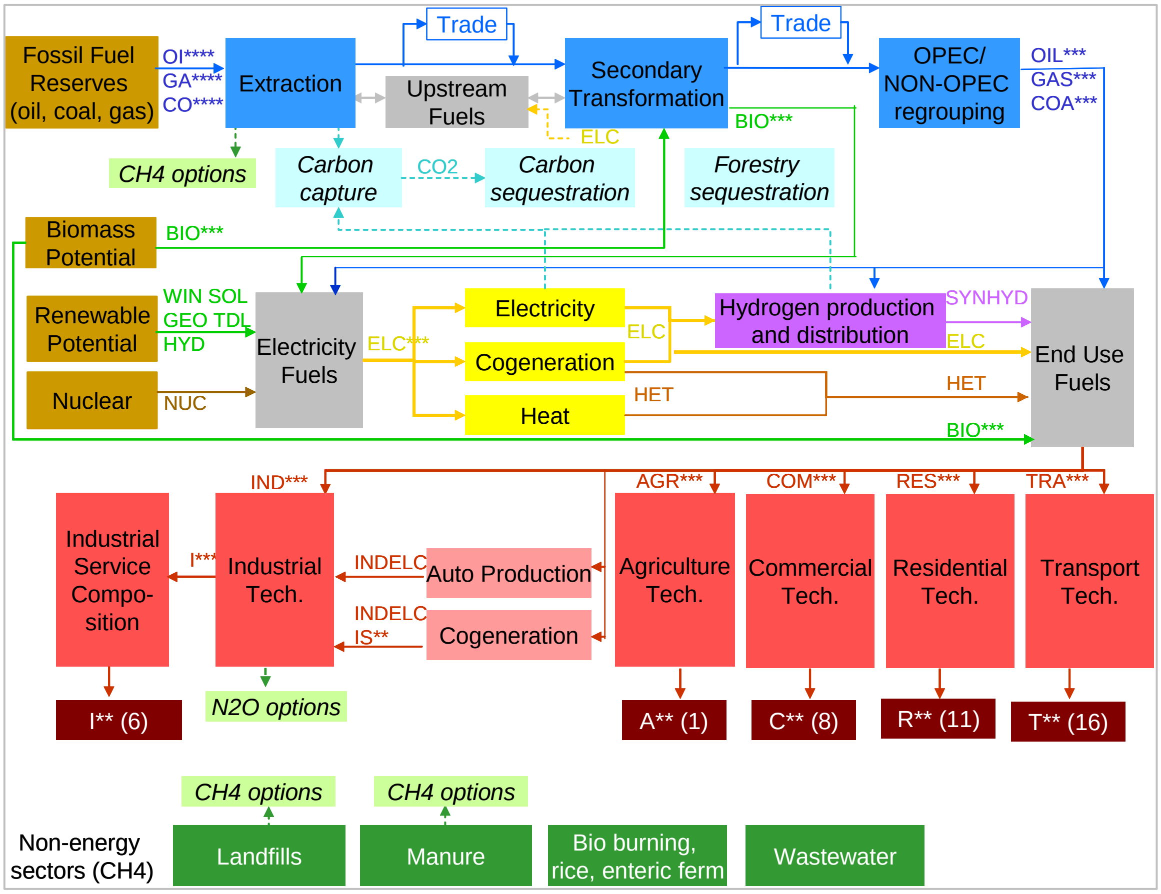

Figure A1. TIAM Reference Energy System

4. Climate

The model includes three series of climate equations, calculating respectively: the concentrations of the three main GHG gases, the total radiative forcing for these and other substances, and the increase in mean global temperature.

- *Concentrations*: The three gases are modeled separately. The CO2 cycle is a three-reservoir model (atmosphere, upper ocean, lower ocean), inspired by Nordhaus and Boyer [16], recalibrated to accommodate the variable-length periods of TIAM. The CH4 and N2O atmospheric cycles are each represented via a single-box model of exponential decay with lives of 9.5 and 119 years respectively, as indicated in [11].

[4] Non-energy CH_4 and N_2O emissions are included in the model (e.g. CH4 from landfills, manure, rice culture, etc.).

- *Atmospheric Radiative Forcing*: the classical formulas for CO2, CH4, and N2O forcings of IPCC [10] are used. In addition, an exogenous forcing is used, to represent the forcing from aerosols, from organic and black carbon, from the non-modeled Montréal gases, and from ozone. The exogenous forcing starts with a value of -0.75 W/m2 [11], and increases linearly by 0.01 W/m2 per year until it reaches 0 in year 2080. Such a profile represents the assumed progressive elimination of aerosols and of Montréal gases during the next 75 years. Finally, total atmospheric radiative forcing is obtained by adding up the above four quantities.

- *Mean global temperature increase*: TIAM includes two recursive formulas that calculate temperature changes in two layers (upper ocean + atmosphere layer, and lower ocean layer), as in [16], recalibrated for TIAM.

TIAM may be used to evaluate different kinds of climate targets: simple emission limits (either yearly or cumulative), concentration bounds, bounds on total radiative forcing, and, finally, limits on mean global temperature change. In order to circumvent the non-convexity of the forcing formulas, linear approximations of each forcing equation are implemented. The approximations are accurate with 3% of the exact values in the ranges considered.