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Pace and direction of economic growth under fossil fuels production constraints

A general equilibrium analysis with the Imaclim-R model

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Abstract

The issue of oil depletion – and more generally of future oil production – took a critical importance after the dramatic increase and collapse of oil prices experienced during the last years. In this study, we try and analyze the macro-economic consequences of a constrained future oil supply. To do so, we compute 768 energy/economy integrated scenarios with the IMACLIM-R model, in order to explore the uncertainty on future macro-energetic contexts as widely as possible. After a statistical analysis of the model outputs, we obtain three robust and quantified results: first, oil production profiles are mostly determined by the supply configuration, while oil prices depend on other economic and technological parameters. Additionally, beyond the amount of recoverable oil resources, sustained investments in the oil sector is a key factor in the oil production profile, and thus on the wealth level which strongly depends on oil production. Second, tensions on future oil production can cause significant GDP losses for all regions, even though developing countries are more affected than the OECD countries. As a matter of fact, oil-exporting countries are also seriously affected by those tensions, despite higher rents in the short-run. Third, climate policies bring a co-benefit to mitigation by reducing the uncertainty on future oil production. Indeed, besides the hedge that they represent against costly climate changes, they could ease wealth losses linked to tensions on future oil supply.

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1 Introduction

The Total company recently issued a world oil production trajectory for the period 2010 to 2030, reaching a maximum value of 95 Mb/d before 2020 (Mosconi, 2008). This vision of oil production future is in strong contrast with usual estimates used by major international institutions: for instance, in the IEA Reference Scenario, world oil production rises by 26%, from 82.3 Mb/d in 2007 to 103.8 Mb/d in 2030 (IEA, 2008), while the Energy Information Administration predicts such high levels as 112.5 Mb/d in 2030 in the Reference case (IEO, 2009). These opposite views on future oil production reflect a more general debate on oil depletion – originally brought into the public debate by non-governmental associations – that took a critical importance after the dramatic increase of oil prices experienced during the last years, triggered by fast-growing demand and insufficient investment in supply infrastructure (according to many energy experts' judgement). As a matter of example, it is worth mentioning ASPO[1]'s forecasts about future oil production (Skrebowski, 2006) which anticipate a peak of oil production in 2010 at 94 Mbd, and the Oil Drum megaprojects (crude oil +NGL) update of the study with a peak around 2010 at 81 Mb/d (Foucher & Staniford 2008).

The impact of such projections on the economic growth is an underworked question, and is impossible to tackle with a pure bottom-up perspective. Yet, these forecasts are mainly constructed by former petroleum geologists or major companies of the oil extracting sector, resorting to a vision on (i) physical and technical constraints affecting oil production and (ii) investment behaviour in oil sector, hence ignoring the feedbacks on the whole energy system. To test macro economic implications of such projections, as well as their impact on the whole energy sector, a given set of assumptions inducing these production curves (related to both physical constraints and behaviors that characterize the evolution of oil supply) should be used in a model parameterization. Once included in a consistent modelling framework, these underlying hypotheses may lead to sudden or progressive disruption in oil production growth (depending on the pattern of oil demand and development of substitute to oil), that would in turn impact more or less economic activity. Of course, the impact of a constrained oil supply on the economy will highly depend on the resilience of the whole energy system to the apparition of depletion constraint on oil production. The overall result thus not only depends on the level of constraint on oil supply but also on the price reactivity of (i) oil demand and (ii) alternative fuel development. Consequently, we will use a hybrid model of the economy (IMACLIM-R) that guarantees the consistency, within the same tool, between the macro-economic and technological evolutions.

One of the difficulties, in addition to the interactions between oil markets and the macro economy, is the results' sensitivity to the model calibration. To overcome this obstacle, we will consider alternative and contrasting macroenergetic contexts to account for uncertainties on several key parameters. Indeed, we aim at delineating and exploring the evolution of the energy system, and assess the implication of constrained oil supply in each of these possible contexts. To do so, we follow an approach in which the model is run

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[1] Association for the Study for Peak Oil and Gas, a network of geologists who work on the date and impact of the peak oil, due to resource constraints

hundreds of times, for different parameterizations, and perform a statistical analysis of the sensibility of output variables to the value taken by key input parameters. We hope that our ability to produce consistent results for a set of visions on the future will allow us to draw robust and interesting conclusions.

This report is structured as follows. In the next section, we will explain the modelling framework and the methodology used to explore the uncertainty. The second section starts with a description of IMACLIM-R and then exhaustively depicts the hypothesis taken on some key parameters describing the uncertainty. In the third section, we will describe the results with a focus on oil markets futures, and question the coping strategies in the eye of future oil depletion. Finally, we will analyze wealth losses in a context of very constrained oil supply, and the hedge that climate policies could provide against those losses.

2   Modelling framework and scenario development

The analysis of interactions between oil markets and the macroeconomy has given rise to a large body of research especially from the first oil price shock of 1973 on. This literature is dominated by empirical econometric studies, traditionally based on a linear cointegration framework, that demonstrate an inverse relationship between oil prices and GDP (see (Brown & Yücel 2002) for a survey). A number of transmission channels have been identified, among which the classic supply-side effect[2] proves to be the most satisfactory explanation of the simultaneous slowing down of GDP growth and the stimulation of inflation created by rising oil prices (see, among others, (Barro 1984; Brown & Yücel 1999; Abel & Bernanke 2001)). However, it fails to reproduce the observed magnitude of the oil-GDP correlation, and does not represent the asymmetric effect of oil prices. Extensions of the basic model have been proposed (see (Hamilton 2005) for a review). They include the adoption of mark-up pricing instead of competitive markets (Rotemberg & Woodford 1996), the capital utilization rate (Finn 2000) or the accounting for frictions in reallocating labor or capital across different sectors that may be differentially affected by an oil shock (see (Atkeson & Kehoe 1994; Bresnahan & Ramey 1993)). Conversely, most studies ignore the role of price-signals as influencing producers' behaviors even though they condition the amount of economically exploitable resources and the incentives for exploration and investments. A noteworthy counterexample is (Rehrl & Friedrich 2006) who integrate Hubbert curves in a model of intertemporal optimal resource depletion, and explicitly account for the influence of price-signals on oil production patterns.

The previous paragraph highlighted the theoretical complexity of interactions between oil markets and the macroeconomic aggregates. Yet these econometric studies which focus on the short-run are inadequate for the purpose of our work: it would be relevant to consider the macroeconomic impacts of a constrained oil supply in a long-run perspective, encompassing alternative fuel supply, carbon-free technologies deployment and development patterns. The modelling framework used in this study was developed to try and overcome the difficulties linked to the endogeneization of these components.

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[2] Rising oil prices affect the economic activity through their effect on a basic input for production. In this case, the elasticity of output with respect to oil prices equals energy's value share in total production.

2.1 Modelling framework: the IMACLIM-R model

IMACLIM-R is a hybrid recursive general equilibrium model of the world economy divided into 12 regions and 12 sectors (Table 1) and solved in a yearly time step (Sassi et al., 2009). The base year of the model (2001) is built on the GTAP-6 database, which provides a balanced Social Accounting Matrix (SAM) of the world economy. The original GTAP-6 dataset has been modified to (i) aggregate regions and sectors according to the IMACLIM-R mapping, and (ii) accommodate the 2001 IEA energy balances, in an effort to base IMACLIM-R on a set of hybrid energy-economy matrixes.

Regions	Sectors
USA Canada Europe OECD Pacific (JP, AU, NZ, KR) Former Soviet Union China India Brazil Middle-East Countries Africa Rest of Asia Rest of Latin America	Coal Oil Gas Liquid Fuels Electricity Air Water Other transports Construction Agriculture Energy-intensive industry Composite (services and light industry)

Table 1 Regional and sectoral disaggregation of the IMACLIM-R model

As a general equilibrium model, IMACLIM-R provides a consistent macroeconomic framework to assess the energy-economy relationship through the clearing of commodity markets. Specific efforts have been devoted to building a modelling architecture allowing easy incorporation of technological information coming from bottom-up models and experts' judgement within the simulated economic trajectories. The rigorous incorporating of information about how final demand and technical systems are transformed by economic incentives is allowed by the existence of physical variables that explicitly characterize equipments and technologies (e.g. the efficiency of cars, the intensity of production in transport, etc.). The economy is then described in both money-metric terms and physical quantities, the two dimensions being linked by a price vector. This dual vision of the economy is a precondition to guaranteeing that the projected economy is supported by a realistic technical background and, conversely, that any projected technical system corresponds to realistic economic flows and consistent sets of relative prices.

The full potential of this dual representation could not be exploited without abandoning the use of conventional aggregate production functions that, after (Berndt and Wood, 1975; Jorgenson 1981), were admitted to mimic the set of available techniques and thus the technical constraints impinging on an economy: it is arguably almost impossible to find mathematical functions flexible enough to cover large departures from the reference equilibrium and to encompass different scenarios of structural changes resulting from the interplay between consumption styles, technologies and localisation patterns (Hourcade,

1993). In IMACLIM-R the absence of formal production functions is compensated by a recursive structure that allows a systematic exchange of information between:

- An annual static equilibrium module with Leontief production functions (fixed equipment stocks and intensities of intermediary inputs, especially labour and energy; but a flexible utilisation rate). Solving this equilibrium at some year t provides a snapshot of the economy: information about relative prices, output levels, physical flows and profit rates for each sector and allocation of investments among sectors.

- Dynamic modules, including demography, capital dynamics and sector-specific reduced forms of technology-rich models, most of which assess the reactions of technical systems to the previous static equilibriums. These reactions are then sent back to the static module in the form of updated input-output coefficients to calculate year (t+1) equilibrium.

Between two equilibriums, technical choices are fully flexible for new capital only; the input-output coefficients and labour productivity are modified at the margin, because of fixed techniques embodied in existing equipment and resulting from past technical choices. This general putty-clay assumption is critical to representing the inertia in technical systems and the perverse effect of volatility in economic signals.

IMACLIM-R thus generates economic trajectories by solving successive yearly static equilibriums of the economy interlinked by dynamic modules. Within the static equilibrium, in each region, the demand for each good derives from household consumption, government consumption, investment and intermediate uses from the production sectors. This demand can be provided either by domestic production or imports and all goods and services are traded on world markets. Domestic and international markets for all goods – excluding labour – are cleared by a unique set of relative prices that depend on the demand and supply behaviours of representative agents. The calculation of this equilibrium determines relative prices, wages, labour, quantities of goods and services, and value flows.

The dynamic modules shape the accumulation of capital and its technical content, that are driven by economic signals (such as prices or sectoral profitability) emerging from former static equilibriums. They include the modelling of (i) the evolution of capital and energy equipment stock described in both vintage and physical units (such as number of cars, housing square meter, transportation infrastructure), (ii) technological choices of economic agent described as discrete choices in explicit technology portfolios for key sectors such as electricity, transportation and alternative liquid fuels, or captured through reduced form of technology rich bottom-up models, and (iii) endogenous technical change for energy technologies (with worldwide learning curves).

In this framework, the main exogenous drivers of economic growth are (total and active) population and labour productivity dynamics. Economic growth is also significantly dependent upon international trade, particularly for energy commodities, and the existence of market imperfections for both labour (wage curve) and capital (constrained capital flows, varying utilisation rates of productive capacities).

The next subsection describes the methodology used to build prospective scenarios and explore the key uncertainties; furthermore, it presents the modelling choices for some

critical dynamics modules. For more details on these modelling choices, the reader should refer to (Sassi et al. 2009).

2.2 Uncertainty analysis

2.2.1 Presentation of the methodology

This study widely explores the uncertainty that surround the ability of an energy system to be resilient to a constraint on oil supply. Due to the complex feedbacks between purely technical dynamics and the evolution of the whole economic system, we follow (Hourcade, 1993) and to use the C-T-L analytical framework that conceptualizes structural changes as the interplay between consumption styles (C), technological choices (T) and localisation patterns (L). To do so, we take advantage of the detailed representation, in the IMACLIM-R model, of the dynamics that drive the energy system evolution and the material content of economic growth. We identify a set of critical fields on which we will explore the uncertainty (e.g. carbon capture and sequestration (CCS) availability, transport content of China's growth, recoverable fossil resources availability and accessibility).

Uncertainty on fields is translated into uncertainty on a wide set of critical parameters in the model[3] (e.g., for CCS, parameters include the date of availability across each region, capital cost when arriving to the market, technology learning rate, maximum socially and technically achievable market shares, etc.). These critical parameters (CP) are input variables that can be modified by the user as part of the calibration of the model, and define the macroenergetic context in which the model run is performed (they must be distinguished from endogenous outputs that result from a model run). One of the counter arguments that can be put forwards against this methodology lies in the combinatory explosion created by all the parameters. Moreover, the results might become unlikely exploitable if a small variation in each input parameter leads to huge divergences in the model outputs. Nonetheless, this legitimate question can be responded with the endogeneisation of technical, macro economic and behavioural parameters. Actually, our methodology is to explore the uncertainty 'ex-ante' on those parameters and then perform 'ex-post' statistical analyses on the model outputs. For example, the maximum possible share of CCS-equipped coal plants over the whole electric sector is a CP, but the actual CCS equipment rate is an endogenous variable that is consistent with carbon shadow prices, electricity demand, etc. From then on, we can be 'optimistic' on a technology deployment and observe that it does not penetrate the markets because of unfit economic conditions.

We identified hundreds of CPs, and two practical choices had to be made to avoid combinatory explosion. First, selected parameters are aggregated into fewer consistent subsets. For instance, all parameters describing the future availability of oil and gas are aggregated into a "oil and gas markets" subset. Then, for each parameters subset, two possible sets of values are defined, with two possible values for each parameter of the subset. As a result, each parameter subset (CPS) has two consistent options corresponding to two combination choices for the values of their parameters. Eventually we distinguish eight subsets covering the major drivers of macroenergetic contexts as a

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[3] Explanation of a more complete list of critical parameters is the purpose of section 2.2.2

combination of assumptions on natural resources, technology availabilities and international economic trends (see Table 2). Each scenario generated by those eight subsets was run as a baseline, and then with a stabilization of CO_2 emissions to 450ppm in 2050. As a consequence the number of scenarios (2^8) was doubled.

Physical constraints and technologies	Oil and gas markets Coal markets Alternative liquid fuel supply Carbon free options for power generation Energy end uses technologies
Strategic choices and behaviors	Middle-East strategy Development patterns
Macro economy	Time length of the current economic crisis

Table 2 The eight parameters' subsets

Our uncertainty investigation differs from classic Monte-Carlo analysis in that we stick to two values of the parameters, implicitly assuming that intermediate values on CPs lead to intermediate values on endogenous results. We perform an exhaustive assessment of all possible combinations of the modalities in the nine subsets (eight plus climate policies), leading to 2^9 (i.e. 512) scenarios, in order to identify to what extent each CP actually influences the results. Our objective is not to define the most probable of those 512 scenarios but to understand some underlying mechanisms.

In the next subsection, we detail the content of each parameters subset and shed light on the underlying modelling principles.

2.2.2 Description of uncertain parameters subsets

2.2.2.1 Oil and gas markets

(i) Oil supply

The modelling structure of oil supply in IMACLIM-R is based on 3 general principles:

First, a physical description of oil resources (expressed in explicit energy units, GBarrel) with a differentiation by region and nature (conventional vs. non-conventional) is used into the dynamic sub-model describing the evolution of oil producing capacities. Oil reserves data are derived from (USGS, 2000; Greene et al., 2006; Rogner, 1997) and those default values were corrected to incorporate Total estimates about oil resources and future field production profile.

Second, an explicit differentiation is made between fourteen (seven conventional and seven non conventional) categories of resources in each region according to the cost of exploration and exploitation. Each of those sub-categories is submitted to specific inertias in the deployment of associated production capacities. Indeed, oil must be discovered before it can be produced, and the temporal availability for production of a given category of oil resource then depends on the characteristics of the discovery process. This latter is submitted to two opposite effects: the information effect (the more an oil field is exploited, the more information about the localisation of remaining resources is obtained) and the depletion effect (the more a field is exploited, the less oil remains in the soil). Following

(Rehrl and Friedrich, 2006), inertias in the deployment of oil producing capacities resulting from the combination of these technical constraints on the discovery process are captured through independent bell-shaped curves that define the time-evolution of oil producing capacities for each category of oil in each region.

Third, the modelling structure makes a distinction between 2 types of oil producers according to their investment behaviours. All non Middle-East countries are supposed to be motivated by short-term return on investments, which implies that they will bring a category of oil reserve into production as soon as it becomes profitable (that is when the selling price on world market exceeds the total cost of exploration and exploitation). From then on, the deployment of production capacities is limited by geological constraints and then strictly follows the corresponding bell shaped curve. These producers are referred to as 'fatal producers'. On the contrary, for Middle-East producers, the situation is different as the amount of their oil resource gives them a market power which permits the adoption of strategical behaviours aiming at the fulfilment of a precise objective (either a price or a market share target). For a given year, Middle-East production capacity is still bounded by the bell-shaped curve but its actual value can be below this limit if the strategy chosen requires a restriction of production. This 'swing producer' behaviour is consistent with past OPEC production which has no longer fit the discovery trend since the 70's oil shocks (Laherrère, 2001).

Inside this oil supply module, we decided to explore the uncertainty on three major characteristics: the amount of ultimately recoverable resources, the investment behaviour of Middle-East oil producer to postpone the beginning of depletion at the oil field scale, and the nature of inertia affecting the deployment of non conventional production capacities.

In each region of the model, ultimately recoverable resources can take its value in a two elements domain: the first value taken by the amount of the world ultimately recoverable resources comes to 3.1Tb (conventional and unconventional oil) while the second one is 15% higher.

To take into account in our analysis that, for a given oil field, the oil production shape will highly depend on the sequence of investments made to postpone the start of the depletion phase, we set two possibilities as to the share of the Middle-East's amount of ultimately recoverable resources that can be extracted before depletion begins. The Middle-East's oil production depletion can thus begin when three quarters of the resources have been extracted – instead of half resources – so that the production follows a plateau-shaped curve more than a bell-shaped curve.

Furthermore, the shape of the curve modelling unconventional oil production capacity can differ, due to inertias in their spread. If the deployment of unconventional oil is assumed to be easy, the curves modelling associated production capacities are similar as for conventional oil. Conversely, if the diffusion of unconventional oil is slower because of specific additional inertias, we represent their production capacities with flatter bell-shaped curves. Therefore, the third parameter of the 'oil and gas markets' subset is the spread of the bell-shaped curve modelling unconventional production capacities.

Assumptions on the amount of recoverable resources and on investments made to postpone the beginning of the depletion phase are combined to build three possibilities (instead of two) for conventional oil: when the amount of recoverable resources is low the

production follows either a bell-shaped curve or a 'plateau-shaped' curve (depending on the investments in the oil sector), while when the amount of recoverable resources is high the production always follows a 'plateau-shaped' curve. Thus, the introduction of a third option for the parameters subset adds 256 simulations to the first 512 ones and brings the number of scenarios up to 768. In order to simplify the results section, we will call option 1, option 2 and option 3 the three options for this subset. Option 1 corresponds to the case with a low amount of resources and a bell-shaped curve (delayed investments), option 2 to the case with a low amount of recoverable resources and a plateau-shaped curve (sustained investments) and option 3 to the case with a high amount of recoverable resources. The parameter modelling unconventional oil production capacities is dependant on the amount of recoverable resources: in option 1 and 2 the deployment of unconventional oils is slowed down while in option 3 there is no inertia.

(ii) Gas supply

Gas world production capacities are put into exploitation to satisfy demand growth until ultimately recoverable resources enter a depletion process. Gas prices are indexed on oil *via* a decreasing indexation coefficient calibrated on the World Energy Model (IEA, 2007). In the first and second options for oil and gas markets, gas prices remain indexed on oil prices whatever their evolution. Of course, in this case, the sharp increase of gas prices – that is initiated by gas resources depletion process – still stands. In the third option, this indexation disappears when oil prices reach 80$/bl: beyond this threshold, the evolution of gas prices only depends on production costs and possibly on the depletion effect, which leads to a sharp price increase (due to an augmentation of the producers' mark-up rate)..

2.2.2.2 The Middle-East strategy

As presented in section 2.2.2.1 the IMACLIM-R modelling structure makes a distinction between 'fatal producers' and Middle-East countries benefiting from market power. As a result, the Middle-East strategy is a critical parameter whose evolution needs to be explored. If a short-run perspective is adopted, Middle-East would cut back production to ensure a high price level and maintain its revenues. But this response has the drawback, for Middle-East, of accelerating the technical change on oil-free technologies and the adoption of energy-sober consumption patterns by oil-importing countries. This hypothesis would be the first option for Middle-East. An alternative market flooding strategy can thus be envisaged, with low short-term prices and revenues losses compensated by higher rents in the long run (the second option). Apart from the strategic issue, these two alternatives could be linked to a vision on the cartel solidity level. In fact, when the Middle-East's coordination is secure, they can agree to cut back production so that oil prices are high; conversely when they are divided they tend to produce more individually, hence lower oil prices. The first short-term price aimed at by the Middle-East is 80$/bl while the second one is 40$/bl.

2.2.2.3 Coal market

The coal is treated separately from oil and gas because of the larger amount of available resources which prevents coal production from entering into a depletion process before the end of the 21st century. We describe price formation on the world coal market with a

reduced functional form which relates price variation to production changes. This choice allows capturing the cyclic behaviour of this commodity market. In the first option, the coal price growth is very sensitive to the coal production growth. On the contrary the coal price growth sensitivity, with respect to the coal production growth, is quite low, so that the coal production growth can be absorbed without prices variations in the second option.

2.2.2.4 Alternative liquid fuels supply

In the IMACLIM-R modelling framework, first and second generation biofuels and Coal-To-Liquid fuels represent the alternatives to refined oil over the 21st century. The penetration of biofuels is modelled by worldwide supply curves published by the IEA (IEA, 2006). These supply curves define the maximum amount of biofuels that can penetrate the liquid fuel market, at a given date and for a given oil refined products' price (including taxes). The supply curves evolve over time to mimic technical improvement in production processes and account for limits to production due to constraint on land availability and conflicts with other uses of biomass (such as food production). In addition, an exogenous maximum constraint – which encompasses other kinds of inertias that could affect the deployment of these technologies – is imposed to the annual biofuel production growth.

Because of these inertias in biofuels deployment, synfuels are believed to become a potentially competitive alternative to oil. In IMACLIM-R, the main share is taken by Coal-To-Liquid (rather than Gas-To-Liquid) because of the abundance of coal resources. The decision to initiate CTL production is captured through a threshold value for oil price above which CTL producers take the risk of launching large scale production. To account for the inertia due to production investments maturation and the time necessary to adapt distribution networks we set a constraint on the penetration rate of CTL on the market even if it is competitive with oil refined fuels. This constraint is gradually taken off as CTL production increases.

The first value taken by this parameter is 200$/bl while the second one is 120$/bl. Since the parameters in a subset vary altogether, if the constraints are low on the biofuels deployment, they are also low on the CTL deployment, so that in the first option biofuels and synfuels are both limited, while in the second option they can both penetrate the liquid fuel market at a large scale. This choice could seem unrealistic but in our perspective it permits the exploration of extreme situations.

2.2.2.5 Carbon free options for power generation

The electric supply module in IMACLIM-R represents the evolution of power generation capacities over time, depending on the amount of available investment and changes in fuel and factor prices. The model anticipates ten years forward the future electricity demand, taking into account past trends of demand, and computes an optimal mix of electricity productive capacities to face future needs at the lowest cost, given anticipations of future fuel prices. Moreover, the modelling structure allows accounting for the physical constraints – in the absence of competitive technology for electricity storage – that hamper the extensive deployment of renewable capacities within the electrical grid due to their intermittent production, especially for solar and wind energy.

We focused our uncertainty analysis on carbon-free technologies (renewable energy generators – simply called renewables – carbon capture, and sequestration (CCS) and

nuclear plants) since electricity decarbonisation can have a strong impact on the oil sector through electric vehicles deployment. The social acceptability and the future technological availability of these power generation modes spark off debates: future deployment, when technically possible, can be constrained by bottlenecks phenomena or political barriers. Our philosophy is not to address those debates but to test for each technology the resulting effective available dates and the maximum penetration rates as critical parameters taking high and low values. We do not balance the options, nor explain exactly why technologies penetration would be limited, but emphasize on the consequences of those limitations on the energy system and their effects on the global economy through the static equilibriums.

Eventually, in the second option, renewable energies, CCS and nuclear energy can penetrate the markets early and at large scale, while their costs drops quickly thanks to learning by doing effects, whereas in the first one they face strong constraints on their deployment.

2.2.2.6 Energy end uses technology

Final demand for oil refined products comes from production sectors and household consumption. The evolution of this demand is of course related to the general level of activity but its ability to adjust to oil prices movements is highly impacted by inertias (i) on the renewal of equipments and (ii) on technical progress in the three major oil-consuming sectors (industry, residential and transport). In these sectors, inertias on equipments are captured by a description in capital vintages, each of them being characterized by an energy intensity and a final energy mix. At each point in time, energy prices affect the selection of new equipments and technology (including technology explicit portfolio for automobile transportation) but not the technical characteristics of the existing ones. The IMACLIM-R framework includes endogenous technical change that relates the price of energy technologies to their cumulative production through the learning curves. Because of the embodiment of technical change in equipments, endogenous technical change captured in IMACLIM-R has to be interpreted as encompassing both R&D and learning-by-doing.

For the transport sector (private cars and freight), technical change interacts with the overall demand for mobility trough the interplay between the following parameters: (i) the total user's costs of the vehicle (ii) the availability of road infrastructures and alternative options (railways, soft modes) (iii) the saturation of the time budget the consumer can allocate to transportation (the so-called Zahavi law (Zahavi & Talvitie 1980)). Other parameters control constraints on the electrical vehicle deployment. This modelling choice allows us to capture (i) the possibility that progress on the efficiency of vehicles generates a rebound effect on mobility demand (Greening et al., 2000) and (ii) that additional traffics can be induced by new transportation infrastructures (Goodwin, 1996). In the residential sector, some parameters rule the learning on VLE (Very Low Energy) buildings, their penetration speed in reaction to the introduction of a carbon price, and fuel switching away from oil in case of high oil prices. Accordingly, in the second option for energy end-use technologies, the deployment of new technologies in the transportation and residential sectors is made easier than in the first option where inertias prevents them from penetrating the markets effectively.

2.2.2.7 Development patterns

In addition to the uncertainty surrounding technological changes, the IMACLIM-R model allows to include contrasting views on development styles adopted in developing countries along with economic catch-up in the next decades. These dynamics are not only determined by pure economic decisions, but also involve political bargaining, households' preferences and are far from the classical 'carbonomics'. Yet, these patterns are crucial in determining economic growth, and its energy content, since they affect countries' need for energy services in sectors such as transport or dwellings. Our parameters subset describes either a 'mimetic' development pattern, in which developing countries want to adopt the western lifestyle, or a less carbon-intensive development pattern. To do so, we take into account infrastructure policies (which encourage or not urban sprawls), agents' preferences for automobile transport and vast individual dwellings (through income elasticities), and logistics organization influencing transport needs in the production/distribution process (e.g, resort to 'just in time', degree of concentration). The reader must keep in mind that endogenous outputs will be influenced by those parameters, while remaining coherent with the economic context, through the resolution of the economic equilibrium.

2.2.2.8 Time length of the current economic crisis

The main uncertainty as to macro economy is the length of the actual economic crisis. We test two alternative lengths: 2 or 5 years.

2.2.2.9 Implementation of climate policies and credibility of public policies

The two options regarding climate policies are the following: in the second option the model calculates a carbon tax enabling emissions to comply with a trajectory stabilizing, in the long term, CO_2 concentration at 450ppm (ie about 550ppm for all gases, see Table 3). In the first option the model follows a 'Business As Usual' trajectory with no constraint on carbon emissions.

Category	CO_2 concentration at stabilization (2005 = 379 ppm) [b]	CO_2-equivalent Concentration at stabilization including GHGs and aerosols (2005 = 375 ppm) [b]	Peaking year for CO_2 emissions [a, c]	Change in global CO_2 emissions in 2050 (% of 2000 emissions) [a, c]	Global average temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity [d], [e]	Global average sea level rise above pre-industrial at equilibrium from thermal expansion only [f]	Number of assessed scenarios
	ppm	ppm	Year	Percent	°C	metres	
I	350 – 400	445 – 490	2000 – 2015	-85 to -50	2.0 – 2.4	0.4 – 1.4	6
II	400 – 440	490 – 535	2000 – 2020	-60 to -30	2.4 – 2.8	0.5 – 1.7	18
III	440 – 485	535 – 590	2010 – 2030	-30 to +5	2.8 – 3.2	0.6 – 1.9	21
IV	485 – 570	590 – 710	2020 – 2060	+10 to +60	3.2 – 4.0	0.6 – 2.4	118
V	570 – 660	710 – 855	2050 – 2080	+25 to +85	4.0 – 4.9	0.8 – 2.9	9
VI	660 – 790	855 – 1130	2060 – 2090	+90 to +140	4.9 – 6.1	1.0 – 3.7	5

Table 3 Characteristics of post-TAR stabilisation scenarios and resulting long-term equilibrium global average temperature and the sea level rise component from thermal expansion only.
Source: Summary for Policymakers of the Synthesis Report of the IPCC Fourth Assessment Report.(IPCC 2007)

Oil and gas markets	Option 1	Option 2	Option 3
	Low amount of resources	Low amount of resources	High amount of resources Plateau-shaped curve (sustained investments)
	Bell-shaped curve (delayed investments)	Plateau-shaped curve (sustained investments)	
	Inertia on non conventionals	Inertia on non conventionals	No inertia on non conventionals
	Gas price always indexed on oil price	Gas price always indexed on oil price	Gas price indexed on oil price until 80$/bl

	Option 1	Option 2
OPEC strategy	Short-term wanted price: 80$/bl	Short-term wanted price: 40$/bl
Coal markets	High sensitivity of price growth with respect to production growth	Low sensitivity of price growth with respect to production growth
Alternative liquid fuels supply	Limited penetration	Few constraints on penetration
Power generation decarbonisation	Difficult decarbonization	Easy decarbonization
End-uses technologies	Limited penetration	Few constraints on penetration
Development patterns	Mimetic development pattern (carbon-intensive)	Less carbon-intensive pattern
Time length of economic crisis	5 years	2 years
Climate policies	Business as usual	450ppm

Table 4 Summary of the parameters alternatives

3   Results

The following results use the 768 computed scenarios and focus on the study of oil production patterns, oil prices and GDP growth. In a first part, we analyze in details oil markets and the robust insights that can be identified. The second part analyses and classifies the possible adaptation strategies to oil production depletion that emerge from our scenarios and the third part considers the impact on GDP related to constraints on oil production and the hedge that climate policies could provide against the potential economic losses.

3.1 Contrasted patterns on oil markets

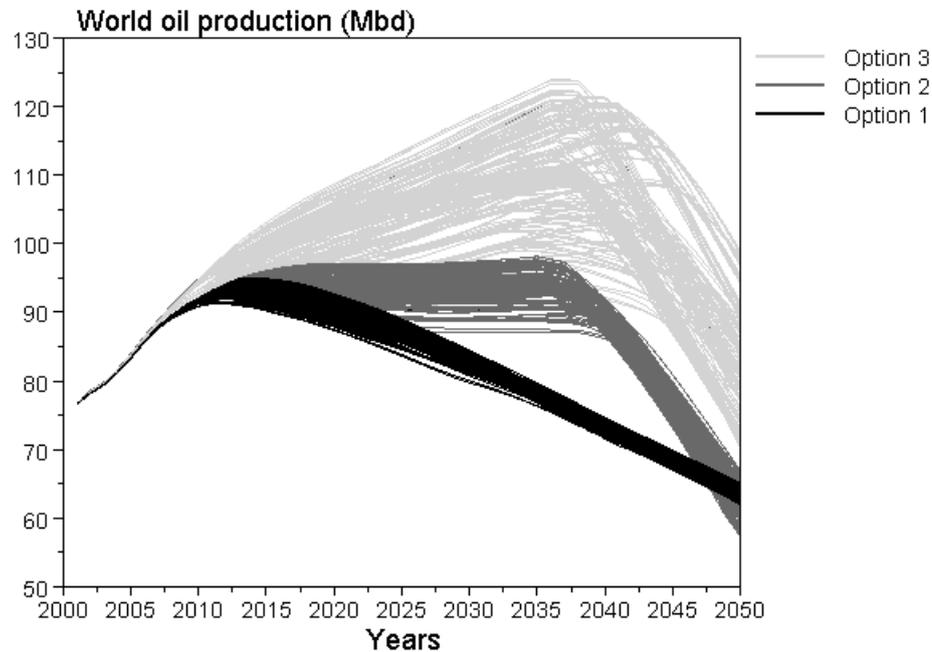### 3.1.1 Oil production profiles

Figure 1: World oil production curves for all scenarios, 2001-2050, detailed according to the 'oil and gas markets' parameters subset.

Figure 1 shows world oil production between 2001 and 2050 for all scenarios, with different colours according to the assumptions made for the parameters subset describing oil production. At first sight these parameters critically determine the shape of the oil production curve, especially when the amount of recoverable resources is low, that is option 1 (delayed investment) and option 2 (sustained investment): within a group of scenarios characterised by the same hypothesis on critical parameters of oil supply, the curves are very much alike. For all scenarios with the option 1 parameterization, the date of peak oil[4] is either 2012, 2013 or 2014 and the mean depletion rate on the post peak period fluctuates on this set of scenarios between 0.7Mbd/year and 0.9Mbd/year. At the end of the period, the mean amount across scenarios of remaining resources is 926 Gb, with a standard deviation of 11Gb.

For scenarios with the option 2 parameterization, variability is higher, especially because the peak oil can be either the beginning of the 'production plateau', or the end: the date of peak oil thus fluctuates between 2012 and 2038 and the mean depletion rate on the post peak period between 0.67Mbd/year and 2.5Mbd/year. This last value is sharp, and corresponds to the option 2 scenarios with the higher oil production peaks, in which unconventionals play an important part: in the 2030's oil prices are high enough for unconventionals to be exploited (oil prices are around 130$/bl in 2030) and then their production enable oil prices to stay below 150$/bl until 2050 (these scenarios correspond

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[4] The peak oil is defined as the maximum of production. Note that when the production curve is plateau-shaped, the date of peak oil does not always correspond to the end of the plateau.

in section 3.1.3, to class 8 of oil prices). These prices stimulate consumption, which leads to a higher peak, and consequently a sharper decrease of oil production: production reaches 97Mbd and the date of peak oil is after 2035. The amount of remaining resources in 2050 is lower for option 2 than for option 1 (813 Gb) because an higher investment to sustain oil production and prevent depletion allows to exploit more oil on the simulated period. However, the variability of remaining resources at the end of the period is higher (its standard deviation is 17Gb *vs.*11Gb for option 1) because adaptation strategies can develop during the 'plateau' phase, thus allowing for more contrasted maximum level of production and making a difference by 2050.

Accordingly, the breathing space for demand driven trajectories is very low when constraints are strong on oil production. Indeed, in all scenarios with a low amount of recoverable resources, an important share of available oil resources is consumed no matter the climate policies, technical optimism or the energy soberness of development patterns (the maximum amount of remaining oil resources in 2050, among all option 1 and option 2 scenarios, is 29% of ultimately recoverable resources). Unexpectedly, it remains true for the most 'optimistic' situation for oil production, meaning option 3, since the maximum amount of remaining resources in 2050 is 31% of ultimately recoverable resources. Nonetheless, variability among scenarios is higher: the mean amount, across all option 3 scenarios, of remaining resources in 2050 is 967 Gb with a standard deviation of 60Gb, so that in some scenarios the remaining reserves in 2050 reach 1.1Tb. Yet, the cumulated production is always superior to option 1 and 2: the minimum across option 3 scenarios of cumulated production between 2001 and 2050 is 1.6Tb, and corresponds to the maximum cumulated production for option 1 and option 2 scenarios. As to the date of peak oil, variability is lower for option 3 than for option 2 since it can occur between 2033 and 2043. Finally, the mean depletion rate on the post-peak oil period fluctuates between 0.96Mbd/year and 3.1Mbd/year, with about the same standard deviation as option 2 scenarios (0.60Mbd/year).

Consequently, even though the level and date of the production peak vary among scenarios because of the different oil sector parameterizations, the situation in 2050 tends to be homogenous with regard to the amount of remaining resources. Nevertheless, fossil fuels prices and the world wealth are very much contrasted in 2050, on account of other parameters subsets such as climate policies or alternative liquid fuel supply.

3.1.2 A focus on the 2001-2030 period: oil production and prices

Figure 2 represents oil production and oil prices for the 768 scenarios between 2001 and 2030. The colours used are the same as in Figure 1, so that they represent the three groups of hypothesis governing oil production. For each group of curves we noted the mean in 2030 and the variation around this mean within the group. For oil production in 2030, variations around means vary between 3% and 12% while for oil prices these variations are from 26% to 30%, therefore in 2030 oil price variability across scenarios is much higher than production variability. In fact, since oil production is physically constrained, oil prices will depend on the demand ability to adapt to the constrained supply.
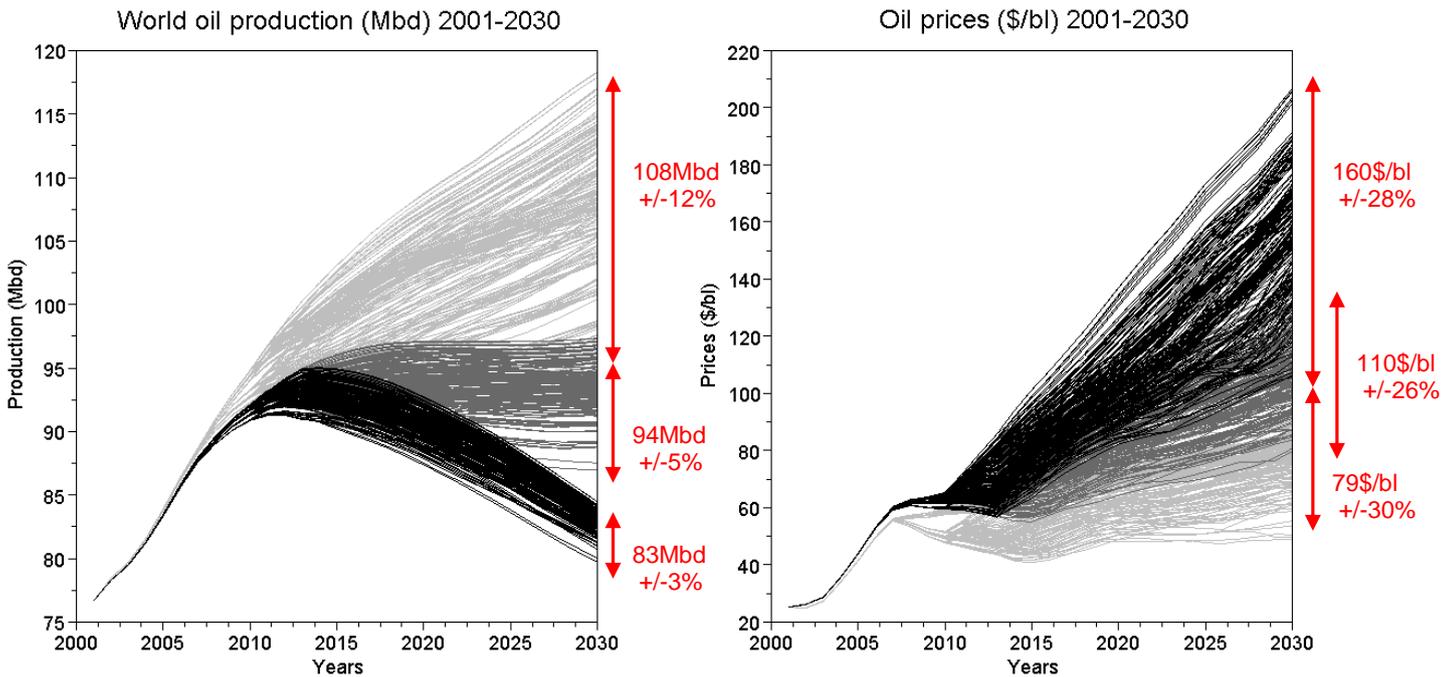
Figure 2: World oil production and prices, 2001-2030, all scenarios.

We notice that by 2030, the more oil production is constrained the higher oil prices seem to rise; nevertheless for the same hypothesis on oil production the oil prices variance is very high, and we would like to understand the contribution of each parameters' subset in oil prices formation in 2030. We thus perform an ANOVA (Analysis of Variance) on oil prices in 2030 (see Figure 3). For each parameters subset the reference case is the first option, except for the 'oil and gas markets' subset for which the reference is the middle option (option 2, see 2.2.2.1). Thus, for every parameters subset the diagram represents the effect of the second option compared to the first one (see Table 4), while for the oil parameters subset the ANOVA compares the two extreme options to the middle one so that the effects of the two parameters 'shape of the curve' and 'amount of recoverable resources' are separated. Note that when we compare option 1 and option 2 the only changing parameter is the shape of the curve while the other parameters (hypothesis regarding gas markets, unconventional oil and the amount of recoverable resources) are identical.

Unsurprisingly this ANOVA confirms that the 'oil and gas' parameters subset is the most determining subset on oil prices in 2030 (Figure 3). Furthermore, the difference between option 1 and option 2 is comparable (even a bit higher) to the difference between option 3 and option 2, which means that one parameter (investment in the oil sector) has as much influence as the combination of all the other parameters of the subset (amount of recoverable resources, shape of the production capacities curve for unconventional oil and gas prices indexation on oil prices). Undeniably, the price increase due to a lack of investment in the oil sector is as important as the price decrease observed when all the other 'oil and gas' parameters are as in option 3. As a consequence, the mean, across

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scenarios with the option 2 parameterization, of oil prices in 2030 (110$/bl) is close to the mean across all scenarios of oil prices in 2030 (115$/bl).
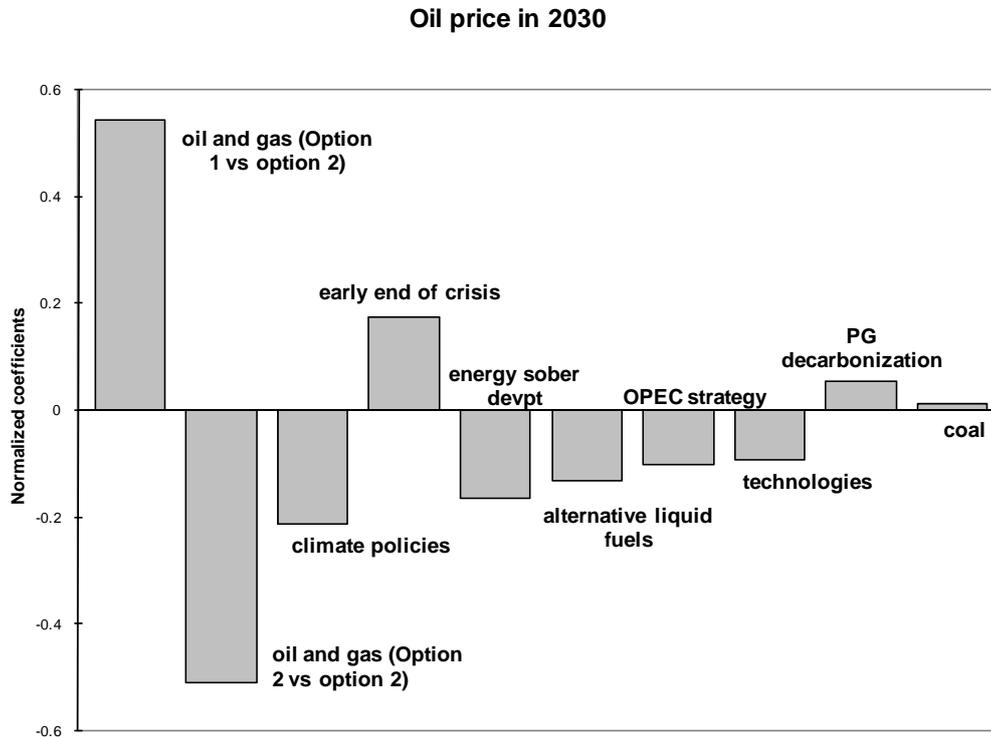
Oil price in 2030

Figure 3 ANOVA on oil prices in 2030. The coefficients are sorted in descending order of influence.

The fact that the 'Power generation decarbonization' subset leads to an increase of oil prices might be surprising, but the reader must remind that this subset contains the hypothesis regarding CCS development, so that when we are in the first option for carbon free options for power generation, the CCS is able to penetrate the markets by 2030. As a consequence, in scenarios with climate policies, and for option 1 for 'PG decarbonisation', emissions constraints are respected and climate policies do not need to tackle the transportation sector in the short run. Thus, oil demand – and so the oil price – is higher than in option 2 'PG decarbonisation' scenarios.

Since the 'oil and gas' parameters are so influent on oil prices, we tried new ANOVAs for each of the three parameterizations (Figure 4), in order to better analyse the other parameters influence on oil prices in 2030. The main result of these ANOVAs concerns the contribution of the Middle-East strategy: the more constrained world oil production is, the less influence the Middle-East gets. Indeed, with the option 3 parameterization the Middle-East strategy is the more influent of all parameters subsets (before the 'climate policies' subset) while with the option 1 parameterization it is the next to last influent parameters subsets (before the 'coal' subset). This is due to (i) the amount of the Middle-East's recoverable resources, which is lower in option 1 and 2 than in option 3, and (ii) the depletion phase in the other regions which begins earlier in option 1 than in option 2 and 3. Indeed, when other regions enter the depletion phase, the Middle-East is limited by its capacity growth, hence the limitation of its market power. As a matter of fact, in order for the Middle-East strategy to be efficient, its capacity growth should be superior to

1.5Mbd/year, which is unrealistic (Saudi Arabia's production went from 10Mbd to 12 Mbd in 4 years).
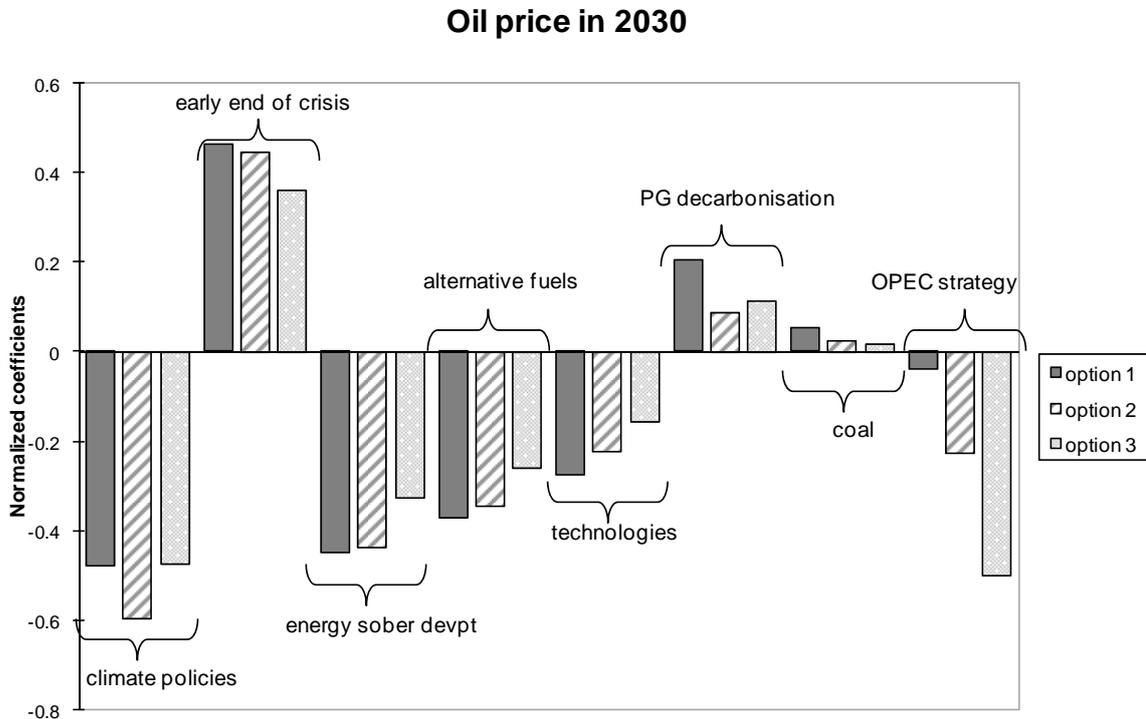
Oil price in 2030

Figure 4 ANOVA for each 'oil and gas' parameterization

For all the other subsets, the order of contribution stays the same, but inside this order the importance of each parameter can vary depending on the 'oil and gas' parameterization. The parameters subsets governing the moderation options for oil demand (*e.g* development patterns, alternative liquid fuels supply and technologies) have an effect all the more important that oil production is constrained. This result is partly due to a time horizon issue: in 2030, oil production is in its depletion phase for option 1 scenarios, so demand moderation and adaptation strategies have a more important impact than in option 2 and 3 scenarios, in which oil is still largely available.

Another interesting result is the contribution of climate policies to the decrease of oil prices in 2030: this contribution, compared to the other subsets contribution, is more important in option 2 than in option 1 and 3. The difference between option 1 and 2 is likely due to a time horizon issue as well: in option 1, since oil production is already in a depletion phase in 2030, climate policies have a smaller impact on oil prices than in option 2; in this case oil production is still in the 'plateau' phase and climate policies have a larger breathing space (they can for example tackle the transportation sector). Conversely in option 3, despite low oil prices, low gas prices enable economic agents to substitute oil to gas, which reduces global emissions, so that climate policies do not need to tackle the transportation sector in the middle-term. As a result, the climate policies influence on oil prices is lower than for option 2, which context is the most favourable to a strong sensibility of oil prices to climate policies (by 2030).

After 2030, the relevance of ANOVAs is less obvious because of the great differences that appear in oil price trajectories between 2030 and 2050. Consequently, in the next section we classify oil price trajectories, to try and understand the combinatory of determinants behind each class.

3.1.3 Classification of world oil prices trajectories

World oil price trajectories between 2001 and 2050 are much contrasted across scenarios and we can barely define the scope of the uncertainty on this output thanks to this exercise. Inside the bounds, a k-means algorithm allows to perform a classification and to identify nine relevant categories of oil prices. These classes are represented by their means curves in Figure 5. In order to avoid boredom for our readers we will not explain all the details behind each class of oil prices but it is interesting to understand the combination of determinants which leads to some of the classes. In Figure 6, Figure 7 and Figure 8, we represented the classes numbered 1 to 6, with the median and 95th percentile of each class.
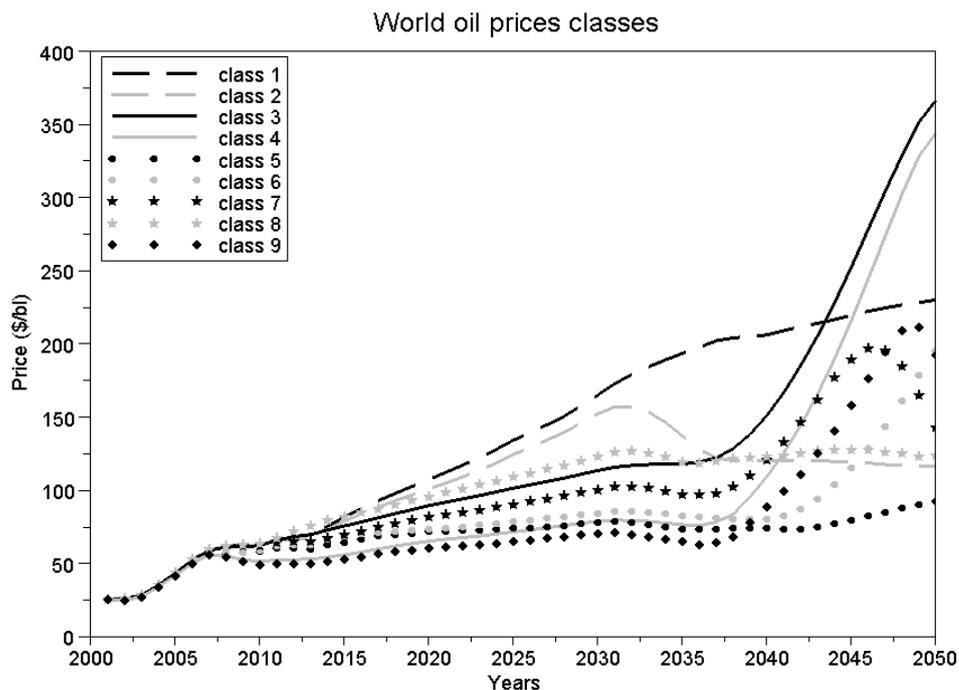

Figure 5 : World oil prices, mean curves [5] for the 9 relevant classes (k-means algorithm).

Figure 6 represents the first two categories in which we find nearly all scenarios corresponding to option 1 for oil (see Table 4). The main difference between class 1 and class 2 comes from the parameters subset describing alternative fossil fuels supply: when biofuels and Coal-To-Liquids productions are parameterized with option 2, which means that we impose a few limitation on their deployment, they become competitive and

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[5] The mean curve represents, each year, the mean of oil prices across scenarios belonging to the same class.

available soon enough to stabilize the oil price around 120$/bl before the end of the period. Oil markets then behave in a 'netback' way with its main competitors in the liquid fuel market that are biofuels and synfuels. Conversely, if we impose more limitation on alternative fuels deployment, alternative fuel supply is not high enough to stabilize the oil price which reaches 300$/bl in 2050 in some scenarios. Nevertheless, it is interesting to note that even though some scenarios are 'optimistic' on alternative fuel supply, some combination of assumptions on the other parameters subsets prevent the oil price from stabilizing; *e.g.* when the following situations are combined: the Middle-East aims at low prices in the short-run, new technologies cannot develop easily, developing countries follow a 'mimetic' development pattern and that there are no climate policies, oil prices keep rising up in spite of the availability of alternative fuels.
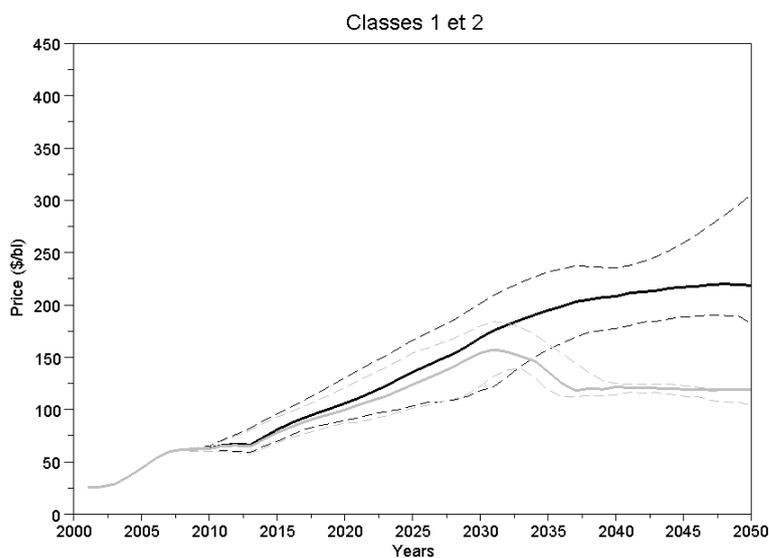

Figure 6 World oil prices: classes 1 and 2

The following classes contain only scenarios in which investment in the oil production sector have been more intensive, no matter the amount of recoverable resources (that is option 2 and option 3 for the 'oil and gas markets' parameters subset, see Table 4).

Figure 7 shows two classes in which all scenarios are pessimistic on the deployment of alternative fuels supply. In class 3 most scenarios have a low amount of recoverable resources (option 2), while in class 4 we find scenarios corresponding to both option 2 and option 3. The price explosion from 2040 can be explained by a rapid depletion of oil production, especially when the amount of resources is low. Nevertheless, in all scenarios belonging to class 4, the Middle-East aims at low short-term prices, so that even if the amount of resources is high, conventional oil productions are maintained elevated until 2030 and substitutes to oil do not become competitive soon enough to prevent the oil price from rising very quickly from 2040 on.
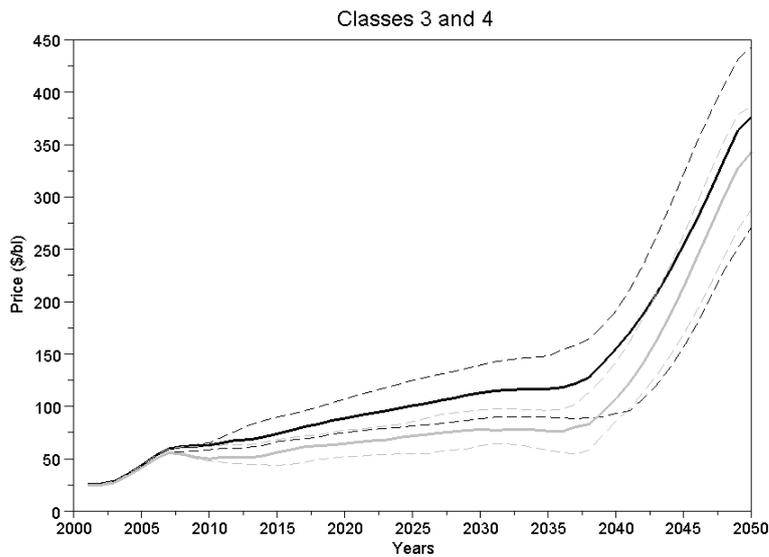
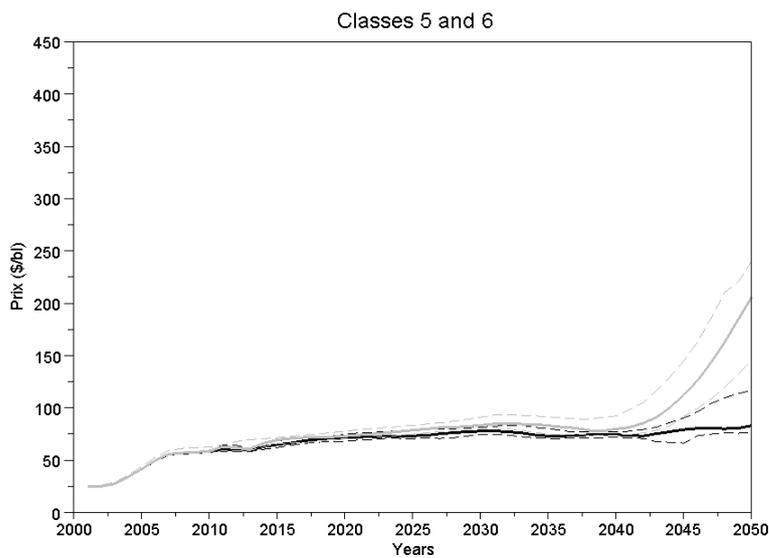**Figure 7 World oil prices: classes 3 and 4**

Figure 8 World oil prices: classes 5 and 6

In Figure 8 we represent two classes containing 138 scenarios in which oil prices remain under 100$/bl until 2040. In both classes the 'oil and gas markets' parameters subset follows option 3 and the Middle-East aims at a high short-term price. The difference between class 5 and class 6 comes from climate policies: in class 5 climate policies are present in all scenarios but not in class 6.

Now that we have seen much contrasted oil futures, in the next section we will see coping strategies in the face of oil depletion.

3.2 Coping with oil depletion

In this section, we focus on the depletion period in scenarios with oil supply context governed by option 2. In those scenarios, because of the 'plateau-shaped' production curve and the low amount of recoverable resources, oil production depletion is sharp. In the face of this depletion, economies have to adapt quickly to a lack of oil supply and we can analyze the different strategies adopted by the economic agents. We use the following decomposition to represent oil production as:

$$Oil\_prod = \frac{Oil\_prod}{LFU\_prod} \cdot \frac{LFU\_prod}{GDP} \cdot GDP$$

where *Oil_prod* is the world oil production and *LFU_prod* the liquid fuels world production. The first term is thus the share of oil production in total liquid fuel production and the second term the liquid fuel content of world GDP.

In Figure 9 we represented the scenarios trajectories for the two energy terms of the decomposition: the *x*-coordinates correspond to the liquid fuel content of world GDP, so that from left to right the energy efficiency increases, and the *y*-coordinates correspond to the part of oil production in total liquid fuels production, so that from top to bottom oil is substituted to other primary energies for liquid fuels' production.
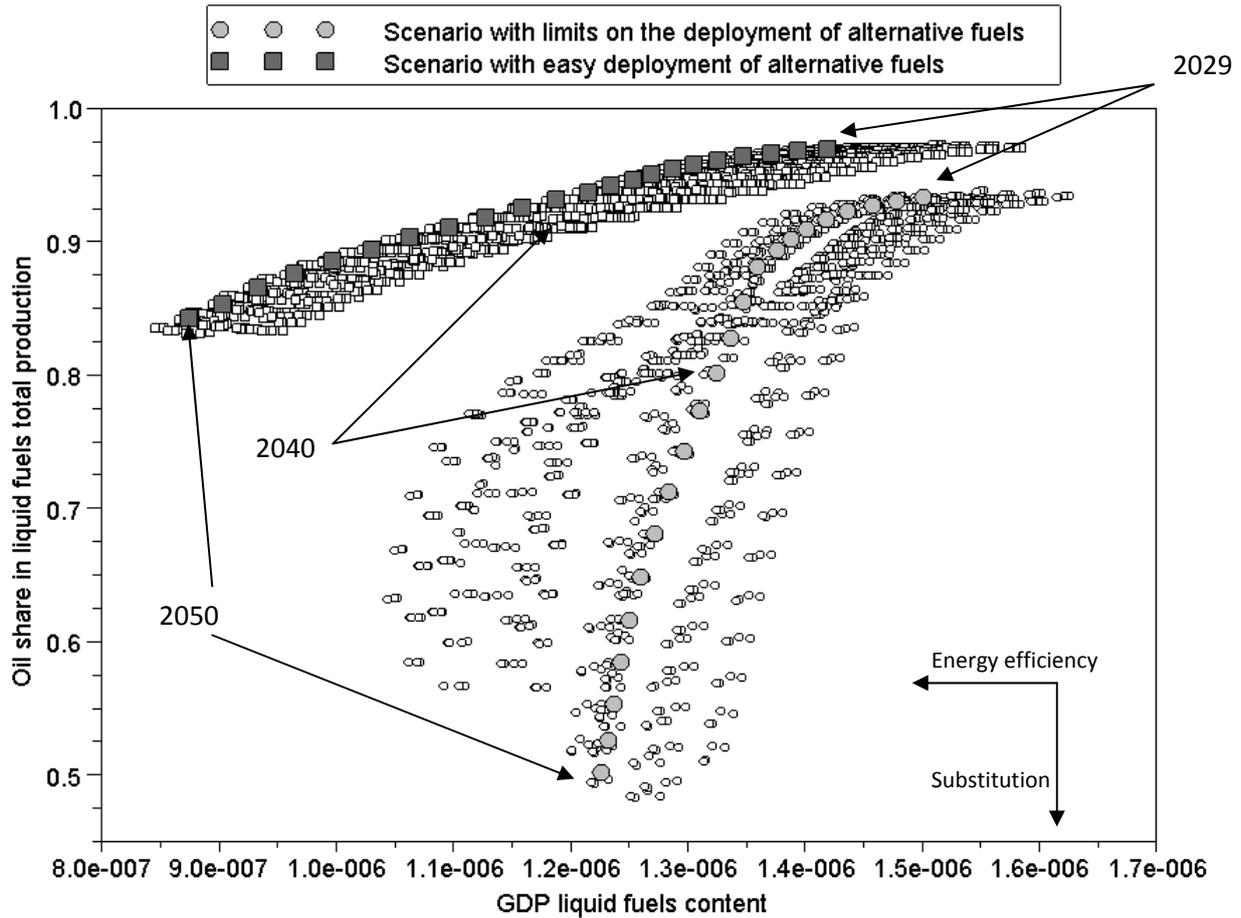These trajectories are represented from 2029 to 2050.

Figure 9 Scenario trajectories in a pseudo-Kaya representation

We distinguish two groups of trajectories, which correspond to the assumptions made on the 'alternative fuels supply' parameters subset[6]: (i) the first group, in which the deployments of biofuels and Coal-To-Liquids are limited, has only one possible trajectory that is energy efficiency but (ii) the second group, corresponding to the second option for biofuels and CTL, have multiple trajectories choices and can arbitrate between substitution and energy efficiency. This result shows that a very constrained deployment of alternative fuels supply locks the economy in a trajectory of energy efficiency when oil production begins its depletion phase, whatever the hypothesis for other parameters groups. On the other hand, if alternative fuel supply is available when oil production declines, many trajectories appear depending on the choices made on technologies and development patterns. For example, the two groups of trajectory on the right-hand side (which use a lot of substitution) correspond to scenarios with sober development patterns and easy new technologies deployment.

In a second approach, we can add the third term of the decomposition (GDP) to the figure. To do so, for each year between 2029 and 2050 we sort the scenario GDPs in increasing order and represent them with a coloured scale (Figure 10).

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[6] We tested all parameters subsets and it appeared that the "alternative fuel supply" CPS was the most determining in the groups of trajectories.
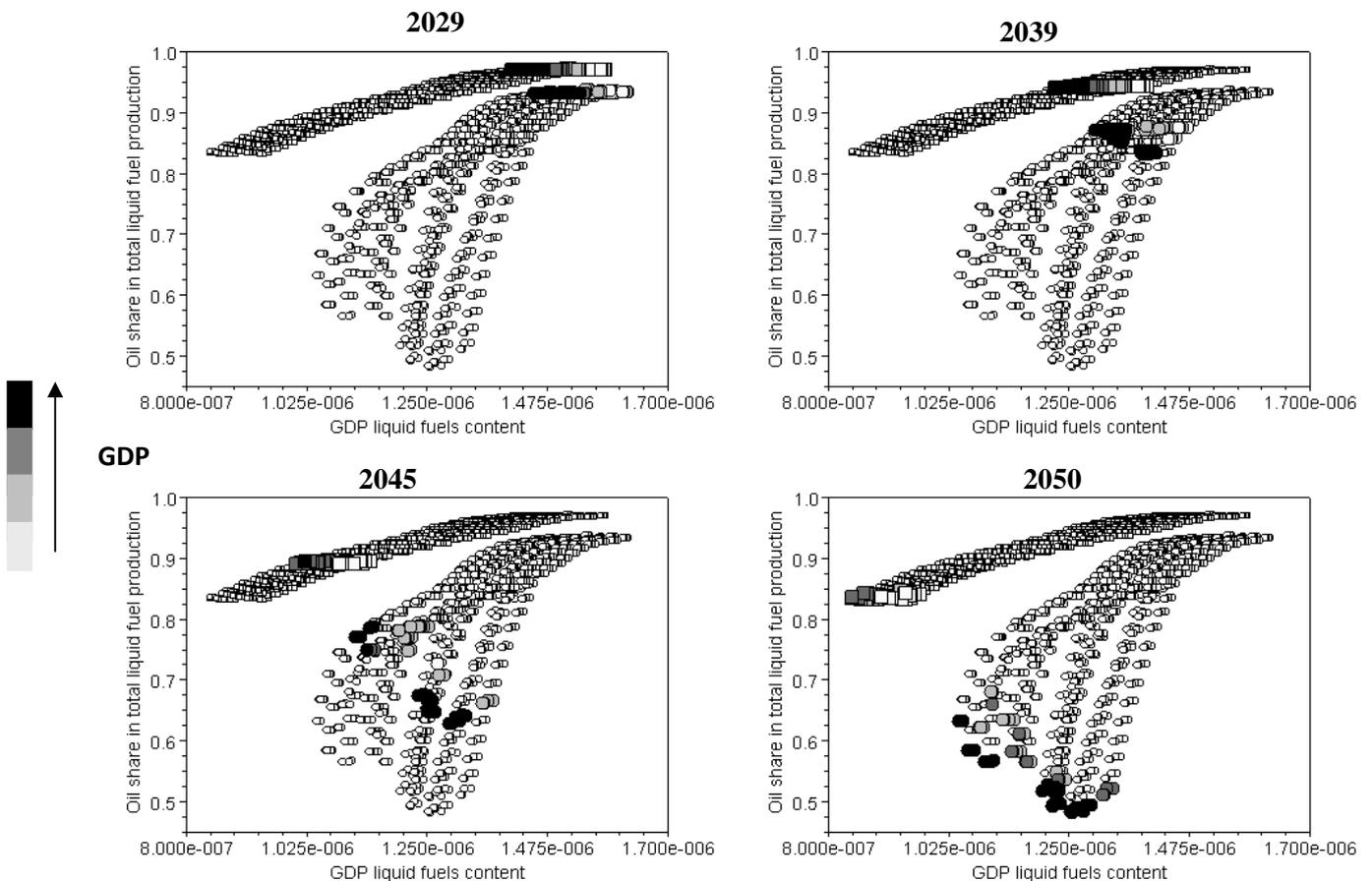
Figure 10 Fourth term of the decomposition: world GDP

We observe that in the first years of depletion, high GDPs are present in both groups of trajectories. However year after year high GDPs are found mainly in the trajectories corresponding to option 2 for alternative fuels and in 2050 all high GDPs are in those trajectories while all the lowest GDPs are in the option 1 trajectories for alternative fuels. This result shows that energy efficiency alone is less efficient than energy efficiency and substitution, since the economies are more constrained and forced to slow down. Conversely, alternative fuels enable to maintain a certain level of growth so that in 2050 the difference between scenarios with and without alternative fuels is significant (the mean GDP in 2050 is 4% higher for scenarios with alternative fuels than for scenarios with constraints on their deployment).

3.3 Macroeconomic impacts of a constrained oil supply

3.3.1 Oil importers: impact on economic activity

The objective of this section is to test the impact of constraints on oil supply on economic growth. To do so, we compare scenarios two by two and compute GDP relative differences for some selected regions between (i) scenarios with the options 1 or 2 for oil supply parameterization (see Table 4) and (ii) scenarios with the third parameterization option (for

one comparison, all other parameters are equal). These dynamics are presented in Figure 11 and Figure 12 for OECD and non OECD countries (excluding Middle East and CIS).
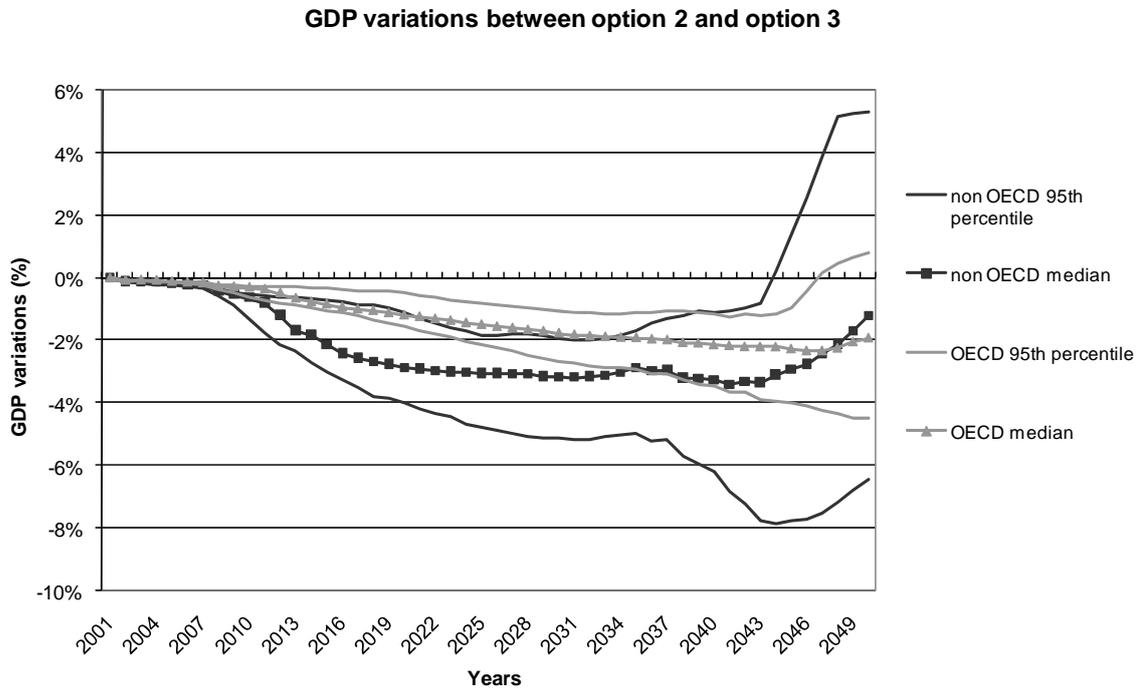
GDP variations between option 2 and option 3

Figure 11 GDP variations due to physical constraints on oil production, option 2 compared to option 3
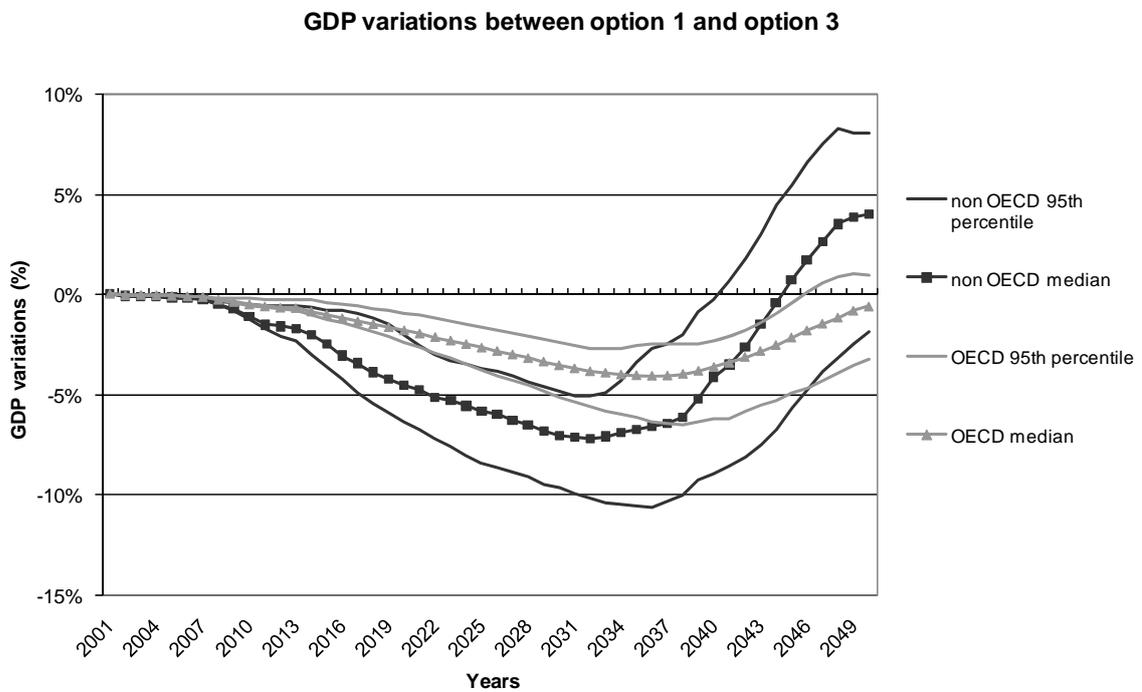
GDP variations between option 1 and option 3

Figure 12 GDP losses due to physical constraints on oil production, option 1 compared to option 3

The analysis of these figures leads to two important conclusions. First, a comparison between OECD countries losses and non OECD countries losses in each graph shows that non OECD countries are much more vulnerable to constraints on oil production than OECD countries. Indeed, in Figure 12 non OECD countries can lose up to 10% GDP in 2035 between a scenario with a high amount of oil resources and the same one with a low amount of resources. This regional difference can be explained by the energy intensity of non OECD countries' GDP, since these countries happen to be in an energy-intensive equipment phase when the peak oil occurs. Indeed, while the OECD economies are based on services, developing countries are in an industrialization process which requires more energy.

On the other hand, their GDP can be 8% higher in 2050 when the resources are low than when they are high, because of the shunning of a huge depletion that can occur in some scenarios with abounding oil resources. Indeed, since in the model anticipations are imperfect, the high oil prices observed in scenarios with option 1 and 2 parameterizations imply a sooner technical change towards oil-free patterns of consumption and production than in option 3 scenarios, in which the economies are surprised by the peak oil around 2040.

A comparison between Figure 11 and Figure 12 shows that GDP losses due to the amount of recoverable resources are lower – for all countries – when investments in the oil sector have been more intensive (and so the production curve is 'plateau-shaped') than when the production curve is 'bell-shaped'. In fact, for non OECD countries the maximum losses between option 1 and 3 is 12%, while it is 10% between option 2 and 3. For OECD countries, the maximum losses are 7% between option 1 and 3, and 5.5% between option 2 and 3. These differences can be explained by two mechanisms: first, intensive investments in the oil sector enable economies to anticipate the depletion phase (thanks to the production 'plateau') and develop oil-free technologies before its beginning, while in option 1 the economic agents must face depletion with no available substitute to oil. Second, in option 2 the postponed peak oil occurs when emerging economies have passed their very energy-intensive phase (in developing countries, the GDP energy intensity is 0.34 toe/M$ in 2030 while it is 0.28 toe/M$ in 2045). More generally, economies are less energy-intensive in 2030 than in 2045 (the world GDP energy intensity is 0.21 toe/M$ in 2030 and 0.18 toe/M$ in 2045), so that they are more vulnerable to a peak oil in 2030 than an oil production with a 'plateau' until 2045. However, in Figure 12 the transition towards oil-independence is hardly over in 2050 while it is not in Figure 11; nevertheless since the economies had more time to adapt to constrained oil production, this transition appears as smoother.

Table 5 gives the same losses but with discounted GDPs between 2010 and 2030[7]. We used two discount rates: 3% and 7%, to follow (OMB, 2003).

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[7] These losses are calculated as the variation between the discounted sum of world GDP between 2010 and 2030 for a scenario with an option 1 or 2 parameterization and the discounted sum of world GDP for the same scenario with an option 3 parameterization for oil supply.

2010-2030	Option 2 compared to option 3		Option 1 compared to option 3	
	Mean	Standard deviation	**Mean**	Standard deviation
OECD	**-1.1%/-0.97%**	0.29%/0.27%	**-1.8%/-1.55%**	0.40%/0.36%
Non-OECD countries (without Middle-East and CIS)	**-2.5%/-2.3%**	0.74%/0.70%	**-4.3%/-3.8%**	1.1%/0.98%

Table 5 Variations of aggregated GDP between 2010 and 2030 (discount rate 3% / discount rate 7%)

This table confirms that GDP losses due to oil production constraints are significant, and the same calculation for the world shows that losses can go up to 3.8% GDP between 2010 and 2030 (with a 3% discount rate) in the most constrained option for oil supply. As a comparison, the mean world GDP losses [8] due to climate policies is 1.0% and these losses can go up to 2.5% in some scenarios. These numbers are consistent with what we can read about climate policy costs, and show that oil production constraints can be more expensive than climate mitigation. Furthermore, in the next section we will see that climate policies could be seen as a hedge against the uncertainty surrounding future oil supply.

3.3.2 Are climate policies a hedge against unforeseen constraints on oil supply?

In a second approach, we separate the scenarios with climate policies (aiming at a 450ppm CO_2 emissions stabilization) from the Business As Usual scenarios, in order to analyse the influence of climate policies on the macroeconomic impacts of oil production constraints.

Figure 13 shows the discounted sum of the world GDP between 2010 and 2030 (discount rate: 3%) for all scenarios and represent the mean of these sums for scenarios with and without climate policies (black or grey stars). As in section 3.3.1, we used both 3% and 7% as discount rate (OMB, 2003) but we only presented results with a 3% discount rate because they are very similar. The x coordinates represent an index of the constraints on oil production from 'not constrained' on the left (option 3) to 'very constrained' (option 1) on the right. For each group of hypothesis on the oil supply context, the bold dotted black line corresponds to the cost of climate policies: the more oil production is constrained, the less climate policies are expensive (1.4% losses for option 3 vs 0.90% for option 1). In fact, when the oil sector is very constrained, the baseline scenarios are less carbon-intensive so that the necessary CO2 emissions reduction is more easily reached, in particular thanks to the depletion of oil production starting before 2030. The main cost difference between option 2 and option 3 is indeed due to the earlier beginning of the depletion phase in option 3, since when investments are not sustained in the oil sector, CO2 emissions due to oil

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[8] These losses are calculated as the variation between the discounted sum of world GDP between 2010 and 2030 for a BAU scenario and the discounted sum of world GDP for the same scenario with a 450ppm stabilization objective. Discount rate: 3%

consumption decrease by themselves (because of high oil prices). Beyond the amount of ultimately recoverable resources, a part of the cost difference between option 3 and 2 is due to rent transfers between oil exporting and oil-importing countries induced by climate policies. Indeed, the ME oil profits are higher in option 2 than in option 3, and they decrease by 11.2% in option 3 because of climate policies, while they decrease by 11.5% in option 2. Consequently, oil-importing countries benefit from a higher rent transfer – measured by the decrease in the ME oil profits – in option 2 than in option 3. Note that although the oil exporting countries' profits are higher in option 1 and 2 than in option 3 (thanks to higher oil prices) their GDP is lower because of a weaker global context and high world energy prices.
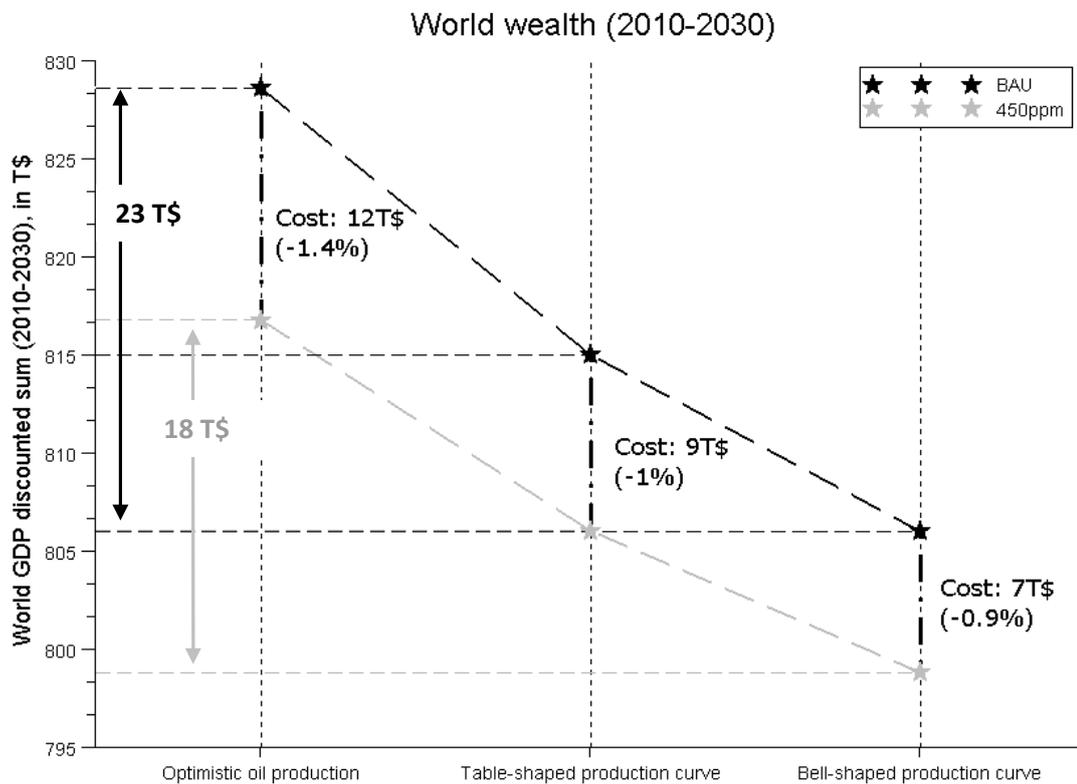

Figure 13 Discounted sum of GDP (2010-2030), 3% discount rate, BAU and 450 ppm CO2 stabilisation, three options for oil supply context.

While keeping in mind that the first aim of climate policies is to prevent from the arising of very costly climate changes, we could focus on the co-benefits of CO_2 emissions mitigation that could arise from improvements in energy security. From this point of view, a key information in Figure 13 is the reduction of the difference between option 3 and option 1 level of welfare when climate policies are introduced: in the BAU scenarios, the difference of wealth between the most optimistic case for oil production and the most pessimistic one is 23T$ while it is only 18T$ in the 450ppm scenarios. Therefore, climate policies bring a co-benefit by reducing the cost of uncertainty on oil production by 5T$, that is 0.66% of

756T$ (mean – across all scenarios – discounted sum between 2010 and 2030 of oil exporting countries GDP).

This co-benefit brought by climate policies can be explained by (i) a better anticipation of oil tensions thanks to higher final oil prices, which prevent the economies from being confronted to a important crisis in the most pessimistic scenarios and (ii) a bifurcation towards less oil-intensive economies whatever the availability of oil. Accordingly, climate policies reduce the uncertainty surrounding future oil supply by limiting the losses in the worst scenarios while preventing the most optimistic scenarios on fossil fuel resources from consuming all exhaustible resources available (and hence from emitting enough CO2 to cause costly climate changes).

4   Conclusion

In this study, we tried and analyzed the macro-economic consequences of a constrained future oil supply. To do so, we computed 768 energy/economy integrated scenarios with the IMACLIM-R model, in order to explore the uncertainty on future macro-energetic contexts as widely as possible. The methodology we used is based on the generation of 768 scenarios, created with a combinatory of values for 9 parameters subsets. After a statistical analysis of the model outputs, we obtained three robust and quantified results: first, oil production profiles are mostly determined by the supply configuration, while oil prices depend on the other parameters subsets. Additionally, beyond the amount of recoverable oil resources, sustained investments in the oil sector is a key factor in the oil production profile, and thus on the wealth level which strongly depends on oil production. Second, tensions on future oil production can cause significant wealth losses for all regions, even though developing countries are more affected than the OECD countries. As a matter of fact, oil-exporting countries are also seriously affected by those tensions, despite higher rents in the short-run. Third, climate policies bring a co-benefit to mitigation by reducing the uncertainty on future oil production. Indeed, besides the hedge that they represent against costly climate changes, they could ease wealth losses linked to tensions on future oil supply.
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The methodology we created for this study offers stimulating future prospects: first, the material given by our 768 scenarios can help evaluating option values for investment in new technologies. Furthermore, we may be able to assess the dates at which each technology is the more profitable, and then define an investment sequence which facilitates the energy transition towards oil-independence. This methodology also allows performing advanced statistical studies in order to determine interactions between parameters' subsets and the effect of these interactions on the model outputs. In addition to that, the question of the scenarios equiprobability is of course to be asked, and can be re-thought in some specific contexts, after having evaluating the interactions between the parameters subsets. We might for example use the Monte-Carlo techniques, and switch our pair domains for samples of parameters values drawn from input distributions, in order to evaluate more precisely the influence of some critical parameters. Eventually, a

systematic sensibility analysis should also be performed so as to guarantee the robustness of our results, in concern to comply with the IPCC demand for their next report.

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