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Peak Oil through the lens of a general equilibrium assessment

ABSTRACT

Peak Oil refers to the future peak of world oil production and its impact on the economy. We assess its date, level and economic consequences using the general equilibrium model IMACLIM-R. This framework captures the technical, geopolitical and macroeconomic determinants of Peak Oil, which emerges endogenously from their interplay under inertia and non-perfect expectations. A range of dates, from 2017 to 2039, is obtained, depending on assumptions about the reserves, the technical inertia affecting production and the market power of Middle-East producers. The bubble of oil export revenues associated with the post-Peak Oil increase of oil price and its economic consequences are also quantified. We delineate the space of parameters (discount rate; degree of optimism about oil resources) under which a low short-term oil price may maximize the objective function of oil exporters (maximisation of oil rent, or of long term consumption).

Keywords: Peak Oil, oil revenues, CGE Modeling

JEL classification: C68, Q32, Q43

Le Peak Oil au travers d'une évaluation en équilibre général

RESUME

Le Peak Oil fait référence au futur pic de la production mondiale de pétrole et à ses impacts sur l'économie. Nous évaluons sa date, son niveau et ses conséquences économiques à l'aide du modèle d'équilibre général IMACLIM-R. Dans ce cadre de modélisation, le Peak Oil émerge de façon endogène comme résultant des interactions entre ses déterminants techniques, géopolitiques et macroéconomiques sous contraintes d'inerties et d'anticipations imparfaites. Nous obtenons un intervalle de dates, de 2017 à 2039, en fonction des hypothèses sur les réserves, les inerties techniques affectant la production pétrolière et le pouvoir de marché du Moyen-Orient. La bulle de profits pétroliers associée à l'augmentation des prix du pétrole après le Peak Oil et ses conséquences économiques sont aussi quantifiés. Cette analyse nous permet de décrire l'espace des paramètres (taux d'actualisation, optimisme sur les réserves) suivant lesquels un maintien de prix bas à court terme peut maximiser la fonction objectif des producteurs pétroliers (maximisation des rentes pétrolières ou de l'activité à long-terme)

Mots-clés: pic pétrolier, revenus pétroliers, Equilibre général

Classification JEL: C68, Q32, Q43

Peak Oil through the lens of a general equilibrium assessment

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Although the popular notion of Peak Oil conveys concerns about the economic consequences of a decline of world oil production, it is remarkable that it still relies on almost purely geological-based analyses (Deffeys, 2002) which extrapolate the Hubbert prediction of a bell-shaped oil production trend for the US (Hubbert, 1956, 1962). But such an extrapolation at a global level is questionable (Lynch, 2003). Total oil production is indeed governed by the economically driven dynamics of supply and demand, and there is no reason why the time profile of oil production, although passing through a maximum, should be nicely bell shaped between the 'zero' of the pre-industrial period and the 'zero' of the after exhaustion period.

However, the Hubbert approach points an important determinant for the macrodynamics of oil markets, namely, the limits on the short term adaptability of oil supply that are imposed by the physical constraints on production flows at the field level. One intuition of this paper is that introducing this constraint into the description of producers'

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decisions helps to understand in what direction Middle-East countries could influence oil prices and oil production through their time-limited market power. We do so in a hybrid general equilibrium model of the world economy that includes imperfect foresight and endogenous technical change assumptions. In a world with imperfect foresight indeed, the combination of uncertainty and inertia on the deployment of oil-free options creates a space for strategic games.

With this insight, we will primarily show the economic consequences of the date and level of Peak Oil in two geopolitical contexts. In the first, Middle-East producers maximize short term oil revenues by limiting the deployment of production capacities; in the second, they deploy these capacities to maintain moderately low oil prices, discourage oil-saving technical change and trigger higher and more sudden prices increases in the post-Peak Oil period. Through extensive sensitivity tests we will map the strategical space of Middle-East oil producers by determining the parameter sets under which they may accept a temporary sacrifice of short-term oil profits to later gain a more important bubble of revenue.

In section 1 of the paper, we justify our modeling options for representing oil markets and their interplay with the general equilibrium mechanisms. Section 2 analyses this interplay for the two alternative Middle-East strategies under median parameter values. Section 3 extends the analysis by envisaging a large set of alternative assumptions on the size of reserves and on the deployment of non-conventional oil.

1. Endogenizing Peak Oil in a second-best economy

An obvious framework for analyzing the exhaustion of a natural resource would be a hybrid offspring of Ramsey's optimal growth model (Ramsey, 1928) and of Hotelling’s (1931) model of exhaustible resources[1]. However, most of the approaches based on such framework predict

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[1] see, for example, Anderson (1972), Solow (1974) and Stiglitz (1974)

a steady decline of production over time, along with an exponential growth of prices (see Krautkraemer (1998) for a review), and fail to represent a peak of oil production. This is because they assume that agents behave with perfect foresight, and hence, perfectly anticipate future scarcity of the exhaustible resource. A notable exception is given by Holland (2008) who demonstrates that a peak of production may occur with this framework if forces that increase the equilibrium production counterbalance the decreasing trend imposed by the depletion effect.[2] Actually, most approaches predicting Peak Oil rely on partial equilibrium analysis of recursive market adjustments between oil supply and oil demand, with no consideration of the feedback of oil markets on economic growth (see Fattouh (2007) for a review).

In parallel, a branch of literature was developed after the first oil shock to look at the inverse relationship between oil prices and GDP through econometric approaches (see Hamilton (2008) for a review). It identified a number of transmission channels to the slowing down of GDP growth after oil shocks, of which the classic supply-side effect proves to be the most satisfactory explanation.[3]

These strands of literature have been largely disconnected, and we try to incorporate their major lessons into a hybrid modeling architecture which facilitates the bottom-up/top-down conversation (Hourcade et al., 2006) by endogenizing the fundamentals of oil markets and their macroeconomic consequences

1.1 Modeling the impact of oil markets on macroeconomic dynamics

The macroeconomic literature on oil shocks shows that predictions of output reduction are greatly improved if at least one of the following model extensions is introduced:

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[2] increasing demand over time; exogenous decrease of production costs due to technological change; incentives for further exploration given by the inverse relationship between marginal extraction costs and reserves; and an increase in production capacity in newly developed sites.

[3] This effect is related to the rise in production costs. In this case, the elasticity of output with respect to oil prices equals energy’s value share in total production.

1. mark-up pricing instead of competitive markets. (Rotemberg and Woodford, 1996) predict the correct magnitude for the effects of an energy price increase on output by introducing this catchy way to capture a set of market imperfections.

2. partial utilization rate of capital. Finn (2000) shows that the observed magnitude of the oil-growth relationship can be recovered in a competitive framework, provided that the complementarity between energy and capital services is accounted for.

3. inertias in the renewal of productive capital. Atkeson and Kehoe (1999) succeed in reproducing the typical drop in output caused by an energy tax by using a putty-clay description of capital (with fixed energy intensity for old vintages)

4. frictions in reallocating labor and capital across heterogeneous sectors. The impossibility of costlessly moving capital and workers across sectors with different sensitivities to oil prices causes heterogeneous levels of idle production capacities (Bresnahan and Ramey, 1993) and of unemployment (Davis and Haltiwanger, 2001) across sectors.

The IMACLIM-R[4] framework includes these four extensions in a hybrid recursive model of the world economy that incorporates information coming from bottom-up models and experts' judgments, and captures the general equilibrium feedbacks between energy and the overall economy through the clearing of commodity markets. One of its specificities is to describe explicitly the interplay between the material base of the economy (consumption patterns, technical choices and localization) and economic mechanisms through a description of the economy in both money-metric terms and physical quantities, the two dimensions being linked by a price vector.

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[4] The version of the IMACLIM-R model used in this paper divides the world economy into 12 regions and 12 sectors. The base year of the model (2001) builds on the GTAP-6 database, which has been modified to accommodate the 2001 IEA energy balances, in an effort to base IMACLIM-R on a set of hybrid energy-economy matrixes. The model is solved in a yearly time step for the period 2001-2050. A detailed description of the IMACLIM-R model can be found in (Sassi et al., 2010).

This dual vision of the economy guarantees that the projected economy is supported by a realistic technical background (infrastructures, equipments) and that, conversely, any projected technical system corresponds to realistic economic flows and relative price sets. Thus conventional aggregate production functions that have long been accepted as mimicking the technical constraints impinging on an economy but are characterized by intrinsic limits (Frondel et al., 2002) have been abandoned. Indeed, it is arguably almost impossible to find mathematical functions flexible enough to cover large departures from the reference equilibrium and a wide spectrum of technical and structural changes (Hourcade, 1993). In IMACLIM-R formal production functions are replaced by a systematic exchange of information between an annual static equilibrium and dynamic modules, which define the recursive structure of the model.

The annual static equilibrium module incorporates the above extensions 1 and 2 through the adoption of Leontief production functions with mark-up pricing and a flexible (partial) utilization rate of production capacities and labor. Demand for every good in each region derives from utility-maximizing household consumption, investment and the intermediate uses of production sectors. The clearing of domestic and international markets for goods provides a snapshot of the economy at date *t*: relative prices, wages, labor, quantities of goods and value flows.

Dynamic modules include demography, capital dynamics and sector-specific modules. The latter are reduced forms of technology-rich models describing the reactions of technical systems to economic information emerging from earlier static equilibrium (including geological constraints at the oil field level). Between two equilibria, only the input-output coefficients of new capital are modified and not those of techniques embodied in equipments resulting from past choices. This putty-clay assumption introduces the above extensions 3 and 4 by representing the inertia of technical systems and endogenizing sub-optimal equilibria due to misallocation of investment under imperfect foresight. These reactions are sent back to the static module in the form of updated input-output coefficients to calculate the *t+1* equilibrium.

IMACLIM-R generates trajectories by solving yearly static equilibria of the economy under evolving dynamic constraints. The growth patterns may depart from the natural growth defined by the dynamics of population and labor productivity (Phelps, 1961) as a consequence of imperfect markets for labor (captured by a wage curve[5]) and capital (capital flows, over or under utilization rate of production capacities) in the presence of imperfect expectations.

1.2 Modeling the long-term dynamics of oil markets

A comprehensive description of oil markets must account for their geopolitical, technical and economic determinants, namely:

a) the geological nature of oil reserves imposes constraints on the deployment of new production capacities and hence on the short-term adaptability of the oil supply.

b) short-term agents' trade-offs between consumption and investment decisions determine the direction of technical change and its oil-intensity.

c) uncertainties in the technical, geopolitical and economical determinants of oil markets that alter agents' expectations, pave the way for strategic uses of uncertainty (Allais, 1953).

d) Middle-East countries (ME) at the core of the Organization of the Petroleum Exporting Countries (OPEC) can influence world oil prices until they approach their depletion constraint.

1.2.1 Oil supply

We distinguish different categories of oil resources according to their production costs (exploration and exploitation) and the nature of the resource (conventional or non-conventional). It is an experimental fact that the production time profile of an oil field is

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[5] see (Guivarch et al, 2010) for a more in-depth analysis of this wage-curve assumption.

constrained by the characteristics of the reservoir, and that accelerating extraction both increases costs and undermines the rate of recovery. In a study of North Sea oil fields, Bentley (2002) shows that the extraction profile usually consists of a 2-3 year fast increase followed by a short plateau and a long-lasting decline. The generality of this profile suggests that producers have limited leeway for modifying the overall rate of extraction at the field level and the aggregation at the regional level leads to a bell-shaped profile. For each oil category, the dynamics of production capacity *Cap(t)* is then described by a bell-shaped curve. Following (Rehrl and Friedrich, 2006), we adopt the following mathematical form[6]:

$$Cap(t) = \frac{Q_\infty . b e^{-b(t-t_0)}}{\left(1+e^{-b(t-t_0)}\right)^2} \tag{1}$$

In equation (1), t is the current date, t_0 the starting date of oil production for this category, Q_∞ the amount of ultimate resources and b a parameter that captures the intensity of constraints on production growth. We retain b=0.061/year for conventional resources as econometrically estimated by Rehrl and Friedrich (2006) and, for the sake of simplicity, the same value for non-conventional resources in the median case. Table 1 summarizes our median assumptions on the amount and distribution of oil reserves, which are consistent with conservative estimates, oil shale excluded[7] (USGS, 2000; Greene et al., 2006; Rogner, 1997).

Total production capacity is recursively determined by summation over the different oil categories. The geological constraints on each oil category captured by equation (1) control the deployment of production capacities and, hence, the adaptability of total oil supply at each point in time (condition *a*).

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[6] In IMACLIM-R, equation (1) is used to describe the deployment of oil production capacities, contrary to Rehrl and Friedrich (2006) who impose the bell-shape curve directly to oil production

[7] Due to the specificities related to the exploitation of those resources and the associated high production cost, we consider oil shale as an alternative to oil instead of a new category of oil

TABLE 1. *Assumptions about oil reserves in the central case (10^9 Barrels)*

Reserves extracted before 2001	**Recoverable reserves beyond 2001**				
	Conventional oil		Non-conventional oil*		
	Middle-East	RoW	Canada	Latin America	RoW
895	780	1170	220	380	400

**Note:* Non-conventional oil includes heavy oil and tar sands

As to the behavior of oil producers, we make a distinction between Middle-East and the non-Middle-East producers. The latter are ‘fatal producers’ and launch investments on new oil fields for a given category of resource as soon as the oil world price reaches a threshold that makes it profitable. Their annual production capacity then evolves over time according to equation (1). If the world oil price falls below the profitability threshold, investment is stopped and the level of production capacity remains constant until the depletion process of the oil fields being exploited begins. Middle-East producers are ‘swing producers’ who fill the gap between fatal producers’ supply and global oil demand. The stagnation and decline of conventional oil in the rest of the world will temporarily reinforce their market power (condition *d*). This allows them to control oil price and revenues through the utilization rate of their capacities: the higher the utilization rate, the higher the scarcity rent for oil producers (Kaufmann et al, 2004). Until they reach their depletion constraints, Middle-East producers can then adapt the deployment of their oil production capacity so that the price of oil reaches a level that satisfies their rent-seeking objective.

1.2.2 Oil demand

Oil demand basically results from the demand for liquid fuels and the availability of large-scale oil substitutes (condition *b)*).

In IMACLIM-R, the short-run price elasticity of final demand for liquid fuels is limited by inertia on *(i)* the renewal of end-use equipment and *(ii)* the pace of learning-by-doing in the three major oil-consuming sectors (industry, residential, transport). This explains why a significant decoupling between liquid fuel demand and economic growth can be obtained only after the renewal of several capital vintages, all the more so where investment choices are taken under imperfect foresight (condition *c)*). In the long-run, further constraints on this decoupling take the form of *(i)* technical asymptotes limiting fuel switching and energy efficiency, *(ii)* limited potentials of non-fossil energies (including political obstacles for nuclear) and *(iii)* increasing dwelling area per capita along with wealth increase. The long-run dynamics of liquid fuels demand is then mainly dependent on the activity level of freight and passenger transportation. The former is driven by the assumption of a constant-in-time transport content of production and distribution, capturing a continuation of current trends in international trade and just-in-time processes. The latter depends on household choice from an explicit portfolio of vehicles and modes. In IMACLIM-R, passenger mobility results from the interplay between *(i)* the total user-costs of a vehicle *(ii)* the availability and relative efficiency of road infrastructures and alternative options (railways, soft modes), and *(iii)* the saturation of the time budget the consumer can allocate to transportation (Zahavi et al., 1980). This modeling choice captures mobility demand induced by new transportation infrastructures and by the rebound effect of progress on vehicles (Greening et al., 2000). For the sake of comparability across scenarios, we consider common assumptions on all the above listed determinants of liquid fuel demand.

Total demand for liquid fuels is allocated between oil and two large-scale substitutes:

- *First and second generation biofuels*: their penetration is based on supply curves given by IEA (2006) which determine their market share at each date given competition with oil (everything else being equal, biofuels are more competitive and their penetration into the market is more prominent when the oil price is higher). The curves evolve in time along with technical improvements and limits due to land availability and competition with other biomass uses.

- *Coal-To-Liquid (CTL)*: As soon as oil prices exceed a threshold value p_{CTL}[8], CTL producers are willing to fill the gap between total liquid fuel demand $D(t)$ and total supply by other sources (refined oil and biofuels) $S(t)$. Their production objective is then $\left[D(t)-\mathrm{S}(t)\right]$. But they may miss this opportunity because of insufficient delivery capacity as a result of past under-investment. Indeed, under imperfect foresight, a period of low oil prices affects the profitability prospects of CTL and discourages investment in this technology. We then consider CTL investment as driven by the current level of oil price and cumulative investment over time is then a function of the sum of past oil price trends: $p_{cum}\left(t\right)=\sum_{i=2010}^{t} p_{oil}(i)$. The share s of the targeted CTL production that is actually realized, given the constraints on production investment, is an increasing function of cumulative investment and, hence, of $p_{cum}\left(t\right)$. As soon as oil price exceeds p_{CTL} , CTL production is given by:

$$CTL\left(t\right)=s\left(p_{cum}(t)\right).\left[D(t)-\mathrm{S}(t)\right] \qquad (2)$$

2. Peak Oil profiles and their economic consequences

To delineate the set of strategic options for Middle-East producers, we use the following two scenarios:

- *The Market Flooding scenario (MF)*: Middle-East producers expand their production capacities and bring the oil price back to its pre-2004 level, p_{low} = 50\$/bl.[9] This floor level maintains stability in the cartel and guarantees a minimum level of income flow to highly populated countries.

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[8] We take p_{CTL}= 100\$/Bbl for all scenarios

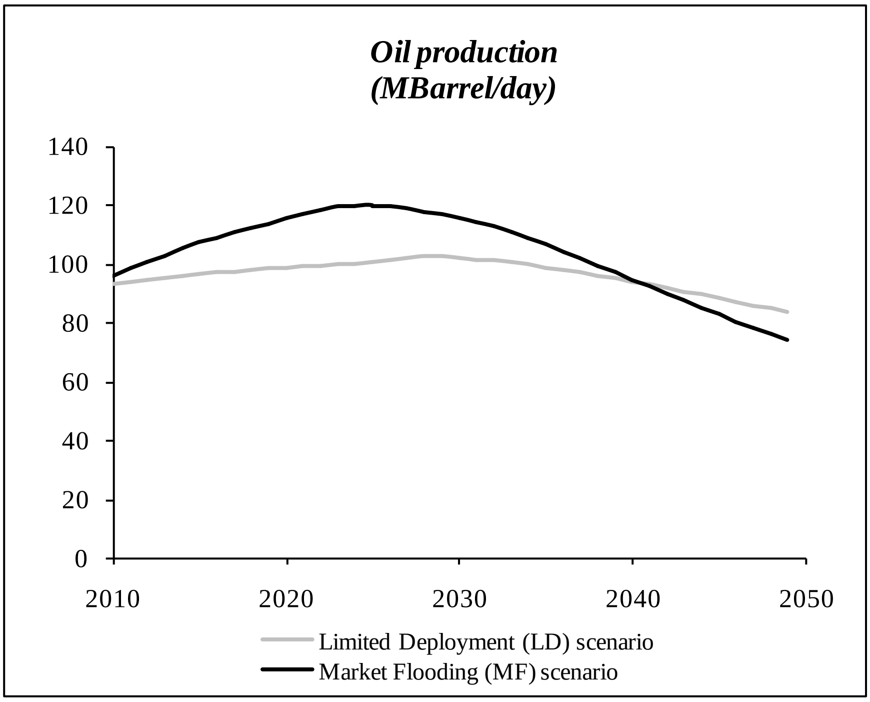
[9] All price levels are expressed in \$2001

- *The Limited Deployment scenario (LD)*: Middle-East producers refrain from investing in new capacity and maintain the medium term oil price around p_{high}=80$/bl. To prevent this high price undermining the stability of the cartel, we introduce complementary local fiscal policies aimed at moderating the cost of oil for consumers within the Middle-Eastern region. [10]

2.1 Beyond Peak Oil: contrasting dynamics of oil markets

The world oil production profile proves to be bell shaped in both scenarios, peaking in 2025 in the MF scenario and in 2028 in the LD scenario (Figure 1). In the Market Flooding scenario oil-intensive patterns of consumption are fostered by low prices which accelerate the exhaustion of conventional reserves. As a result, Peak Oil is brought forward.

FIGURE 1.*World oil production in the two scenarios (MBarrel/day)*



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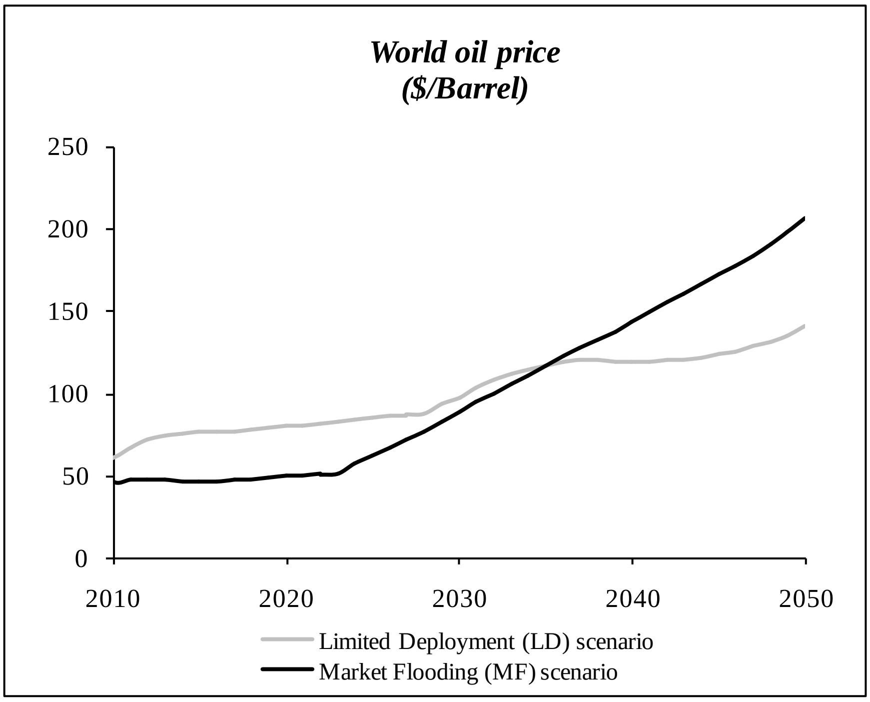
[10] The values of p_{low} and p_{high} correspond respectively to around 60$/bl and 100 $/bl in current currency. They represent a low and high value for medium-term oil price, around the estimate of 78$/bl by the Short-Term Energy Outlook 2010 (available at: *http://www.eia.doe.gov/emeu/steo/pub/contents.html*).

The small gap in the dates of Peak Oil masks important differences in the production profile. The peak level is significantly higher in the MF scenario (120 Mbl/day vs 102 Mbl/day in LD) and the reversal of production trends around Peak Oil is more abrupt (the production declines by 31% in the MF scenario and only 17% in the LD scenario over the twenty years following the 'Peak Oil'). Both these features are explained by the lower energy prices in the first period which *(a)* induce intensive consumption in the early phase *(b)* cause faster exhaustion and a sharper decline of conventional oil, and *(c)* deter early investment in non-conventional production capacities, thus limiting their contribution to total oil production in the post-Peak Oil period.

FIGURE 2. *World oil price ($/Barrel)*

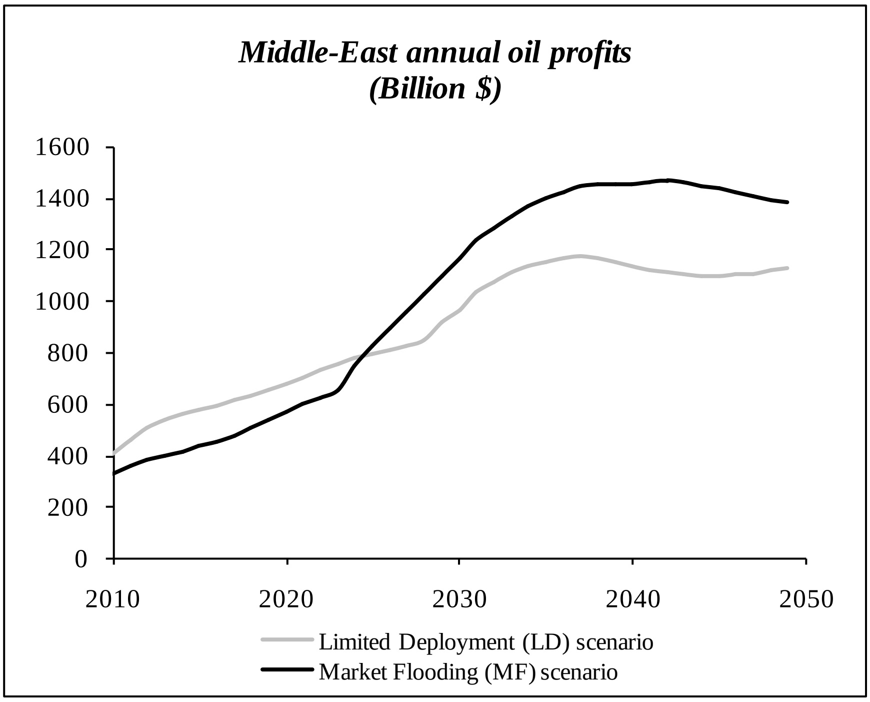


The MF scenario succeeds in maintaining low prices for the first fifteen years of the projected period before a steep and lasting increase in oil prices begins just before Peak Oil. It is triggered by tension between high demand that is difficult to reduce overnight, and the constraints on oil production capacity and deployment of oil substitutes. Conversely, prices in the LD scenario increase smoothly and are lower than prices in the MF scenario after 2035 because high early price signals foster a timely penetration of oil substitutes and energy efficiency (see Figure 2).

2.2 The terms of the trade-off for oil producers

The time-profile of Middle-East oil profits results from the volume and price effects described above. In both scenarios, the post-Peak Oil rise of oil prices induces higher oil revenues, but profits are amplified in the MF scenario by importing countries being locked into oil-intensive growth patterns (Figure 3). This is the reward for sacrificing short-term revenues, and the terms of the trade-off for the Middle-East countries will depend on their objective function.

FIGURE 3. *ME annual oil profits ($10^9$$)*



If Middle-East oil companies act as profit maximizing firms independent of any political influence, the trade-off is based on discounted cumulated oil revenues, and depends on the discount rate. Table 2 shows that the Market Flooding strategy would be superior only for discount rates lower than 6%, which is far below the high internal rates of returns demanded by private oil companies (17.26% to 21.97%, according to the Texas Comptroller's Property Tax Division[11]). Even though the recent financial crisis casts doubts upon the maintenance of so high a profitability ratio, a breakeven point as low as 6% suggests that the adoption of a MF scenario is very unlikely.

TABLE 2. *ME's discounted oil profits (10^9 \$)*

Discount rate	*Limited Deployment Scenario*	*Market Flooding Scenario*
0%	38.9	**43.6**
1%	28.9	**31.8**
2%	21.9	**23.6**
5%	10.6	**10.8**
6%	**8.7**	8.6
7%	**7.2**	7.0
15%	**2.4**	2.2

Let us now assume that Middle-Eastern oil companies and sovereign funds consider broader government objectives, such as calming down short term social tensions or building infrastructure capable of ensuring sustainable development beyond the 'oil era'. In this case, the objective function is households' surplus *S*. Table 3 reports its variation, ΔS, between the two scenarios as defined by $\Delta S = \Delta R - CVI$, where ΔR and CVI are the effective and compensative variation of income respectively, the latter capturing the effect of relative prices on welfare and measuring the amount of income that would leave utility unchanged. Unsurprisingly, high discount rates still favor the Limited Deployment (LD) scenario. However, the range of discount rates for which the Market Flooding scenario is desirable is

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[11] Determination of 2002 Discount Rate Range for Petroleum and Hard Mineral (*available at*: *http://www.window.state.tx.us/taxinfo/proptax/drs02/)*

much wider than with the oil profit maximization criterion: $\left[0\%-13\%\right]$ instead of $\left[0\%-7\%\right]$. The optimization of macroeconomic effects thus makes the MF scenario a workable alternative, all the more so as the social discount rate is lower than the private one.[12]

TABLE 3. *Difference in Surplus in the CS scenario with respect to the CE scenario (10^9 \$)*

Discount rate	*Discounted surplus in LD w.r.t. MF*
5%	-1862
10%	-251
13%	-30
14%	+3
15%	+26
20%	+58

The difference between these two results originates in the long term effects of the two investment strategies. Long-term economic activity and welfare in Middle-East countries depend on a progressive transition away from oil-based revenues towards industrialization. For a given exogenous assumption about the balance of payments, high short-term oil export revenues in the LD scenario imply a higher exchange rate for local currencies which foster the importation of industrial goods at the expense of local production. Conversely, in the MF scenario, the same mechanisms force the development of local industrial production which partially offsets lower oil revenues in the short-term, and better prepares Middle-East economies for the post oil era. In this case, short-term inflows of oil revenues come at a pace compatible with the absorption capacity of the local economy, and the high post-Peak Oil inflows fall into a more mature industrial structure. This captures in a simple form the ‘natural

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[12] Adelman (1986) studies in more detail the specific case of major oil producing countries. He identifies a number of forces tending to lower the discount rate (including weak geological risk due to the size and nature of the fields, and support of oil profits by the nation-owner’s political decisions).

resource curse' (Sachs and Warner, 2001) and demonstrates the role of 'Dutch Disease' mechanisms i.e. that high resource rents do not guarantee sustainable growth patterns if limits in the absorption capacity of the economy weakens the efficiency of re-investment in non-rent production sectors.

2.3 The adverse effects of cheap oil on oil-importing countries

Over the period 2010-2050, average GDP growth rates in the OECD are 1.57% in the LD scenario *vs.* 1.53% in the MF scenario, which corresponds to a 0.92 % difference in terms of discounted consumption[13] and 15 months of growth delay. This difference in favor of the scenario with high early oil prices indicates that more advanced cumulative oil-saving technical change fostered by high pre-Peak Oil prices proves beneficial during the long-term period of scarce and expensive oil.

These aggregate figures hide social consequences of the two scenarios. These consequences can be derived from the time distribution of the difference between effective and natural growth rates. An effective growth lower than (or very close to) its natural rate risks social tensions from low wages and/or high structural unemployment where labor markets are imperfectly flexible. The difference between the two scenarios is analyzed in Table 4.

TABLE 4. *Average growth rates in OECD (%)*

		Total (2010-2050)	Short-term Period (2010-2025)	Peak Oil Period (2025-2040)	Long-term Period (2040-2050)
Natural growth rates		1.42%	1.69%	1.30%	1.19%
Effective growth rates	Limited Deployment scenario	1.57%	1.93%	1.43%	1.24%
	Market Flooding scenario	1.53%	2.00%	1.29%	1.18%

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[13] with a 2% pure time preference coefficient

During the “pre-Peak Oil period”, the MF scenario logically allows for higher OECD growth rates thanks to cheaper oil imports, but the effective growth still exceeds natural growth over the period, even in the LD scenario. During the “Peak Oil period”, the slowing down of economic growth starts sooner in the MF scenario and is more intense because Peak Oil hurts a more oil-dependent economy. In this case, effective growth rates fall below the natural one for 10 years (2030-2040) in the MF scenario. Finally, in the “long-term period”, economic activity is notably more sustained in the LD scenario, thanks to more advanced technical change, whereas, in the MF scenario, the effective growth rate remains below its natural value between 2040 and 2047.

This analysis leads to the counter-intuitive conclusion that low energy prices are not necessarily beneficial for oil-importing countries. On the contrary, to avoid intertemporal losses and strong variability of economic activity, OECD countries may benefit from creating a hedge against the uncertainty of future oil supply by adopting measures, including local fiscal policies or broader international agreements[14], to correct the biased indication on long term oil scarcity.

3. Uncertainties and their strategic implications

After disentangling the mechanisms at play around the Peak Oil perspective by focusing, for clarity sake, on ‘median’ assumptions for major determinants of oil markets, let us now come to a quantitative assessment of the date of Peak Oil and the likelihood of either strategy being used by Middle-East countries. We use sets of alternative assumptions on:

- the (regional and total) amount of oil reserves. Given controversies between pessimistic and optimistic views about ultimate recoverable reserves, we test a number of

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[14] Rozenberg et al (2010) study the role of climate policies in creating a hedge against the uncertainty of future oil supply.

alternative scenarios in which the amount of reserves is a weighted average between two extremes. We retain 3500 GBl (2300 Gbl remaining conventional and 1200 Gbl non conventional resource[15]) as a higher bound and 2400 Gbl (1600 Gbl conventional and 800 Gbl non conventional) as a lower bound.[16] The weighting factor *m* takes the value 0 and 1 for the lower and higher bounds respectively, and 0.5 in the central scenario analyzed in section 2.

- the inertias affecting the deployment of non-conventional production. We consider four values of the parameter *b* to represent the geological, technical and geopolitical uncertainties on the rate of deployment of non-conventional oil, a higher *b*-value translating into easier exploitation and faster deployment of non-conventional reserves. In addition to the median case value (b=0.061), we consider 0.07; 0.05 and 0.04.

To understand how the strategic space of Middle-East producers is affected by these assumptions, we first have to assess how they change the date of Peak Oil and the time profile of oil prices.

3.1 Early or late 'Peak Oil'?

Figure 4 displays the dates of Peak Oil as a function of the size of oil reserves and of the rate of deployment of non-conventional oil. It shows that Peak Oil is reached no later than 2039 under the most optimistic assumptions, compared to 2017 under the most pessimist ones. This range of dates is much wider than the 3 years of difference between MF and LD in the median case. The impact of Middle-East's strategy on the Peak Oil date is negligible in the scenarios with the tightest technical constraints (one year), while more significant with the laxest ones. But, even in this case, it explains less than one third of the overall 22-years difference.

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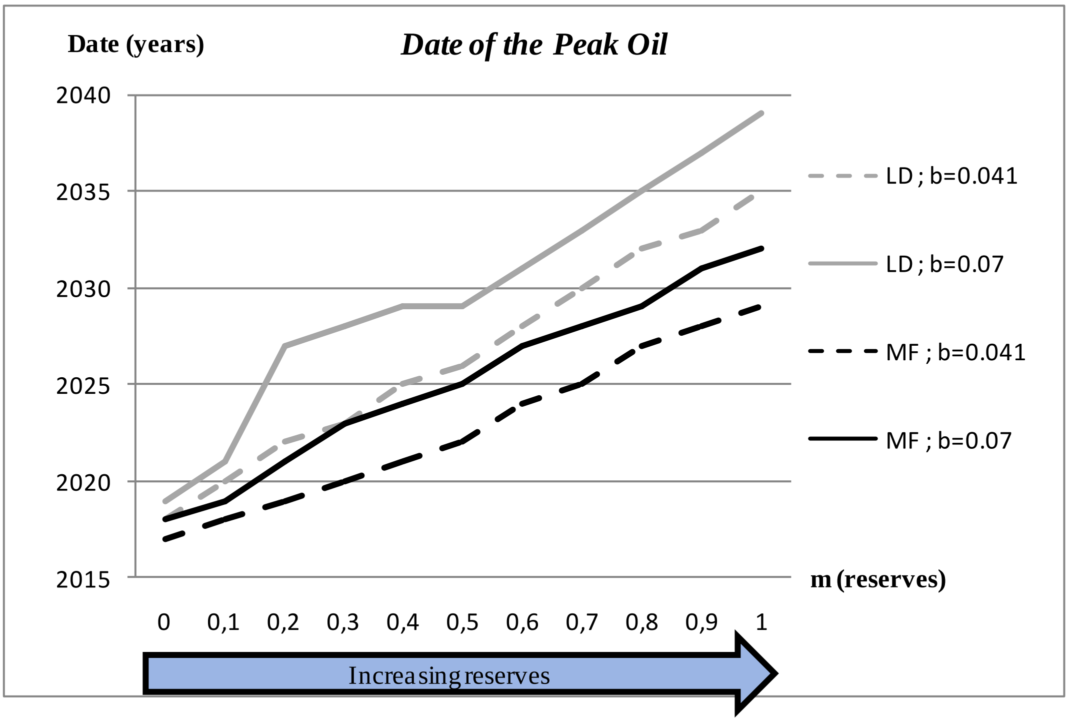
[15] IEA (2008) gives a range for non conventional resources from 1,000 to 2,000 Gbl.

[16] Although quite low, this value is still higher than the1742 Gbl (1027 Gbl conventional, 715 non-conventional) predicted by the Association for the Study of Peak Oil (ASPO) (*available at:* http://www.aspo-ireland.org/contentFiles/newsletterPDFs/newsletter24_200212.pdf)

Unsurprisingly, the size of the ultimate oil reserve is the major determinant of this 22 year range, as shown by the strong increase of all curves from left to right in Figure 4. As to uncertainty about the rate of deployment of non-conventional oil, it creates a difference that can reach six years when the reserves are large. Indeed, other things being equal, lower inertia (a higher *b*-value) facilitates the deployment of non-conventional production capacity that can offset the depletion of conventional reserves and postpone Peak Oil.

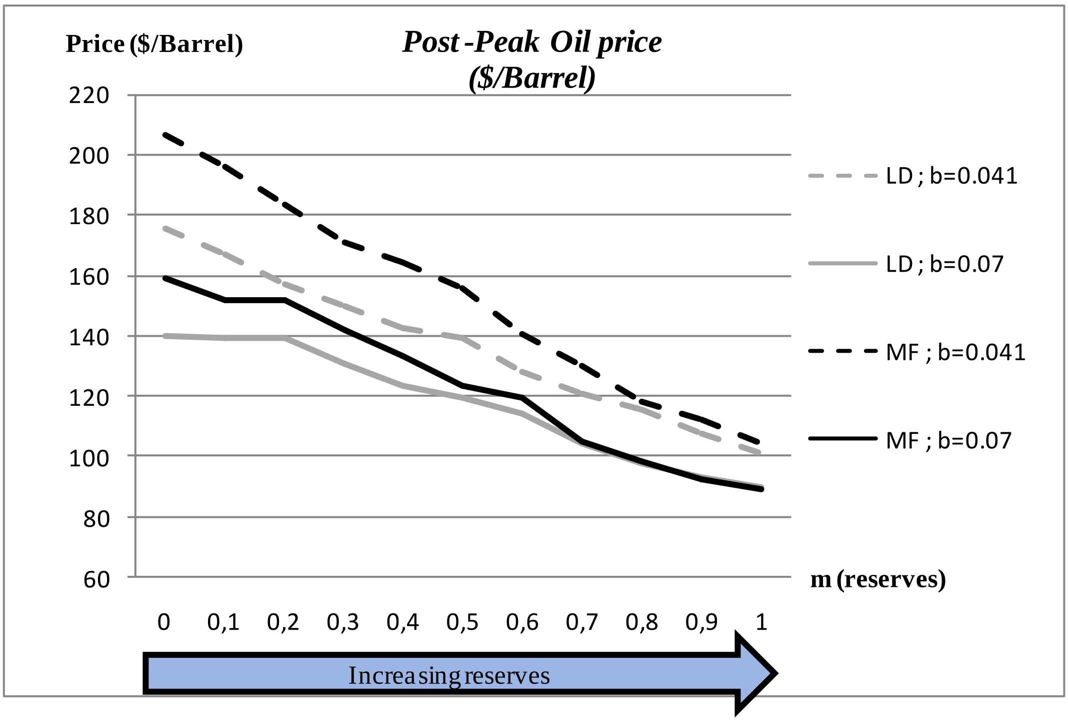
FIGURE 4. *Sensitivity of the date of Peak Oil with respect to the amount of reserves and inertia in the deployment of non-conventional reserves*



3.2 Long-term oil prices after Peak Oil

Two main insights can be derived from figure 5 which displays the average value of oil prices in the post-Peak Oil period. First, higher ultimate resources result in lower long-term oil prices: they give a longer period for deploying oil-saving technical change before Peak Oil, make the economy less oil-dependent at the time of Peak Oil and, subsequently, allow for a less sharp depletion of reserves. Second, long-term prices are always higher under a Market Flooding (MF) scenario. Misled by low price-signals, early choices reinforce long-term oil dependency in this scenario and ensure a high utilization rate of oil production capacities resulting in high long-term oil prices. This difference between the two scenarios is higher with low reserves (early Peak Oil goes along with higher oil dependence at the Peak Oil date) and tends to vanish in the most optimistic cases of high reserves and low inertia. In those cases, Peak Oil happens later, the economy is less oil-dependent, and non-conventional reserves can enter in time to moderate tensions caused by the decreasing trend of conventional production. With high inertia, oil-intensive demand and strongly constrained supply boost oil prices.

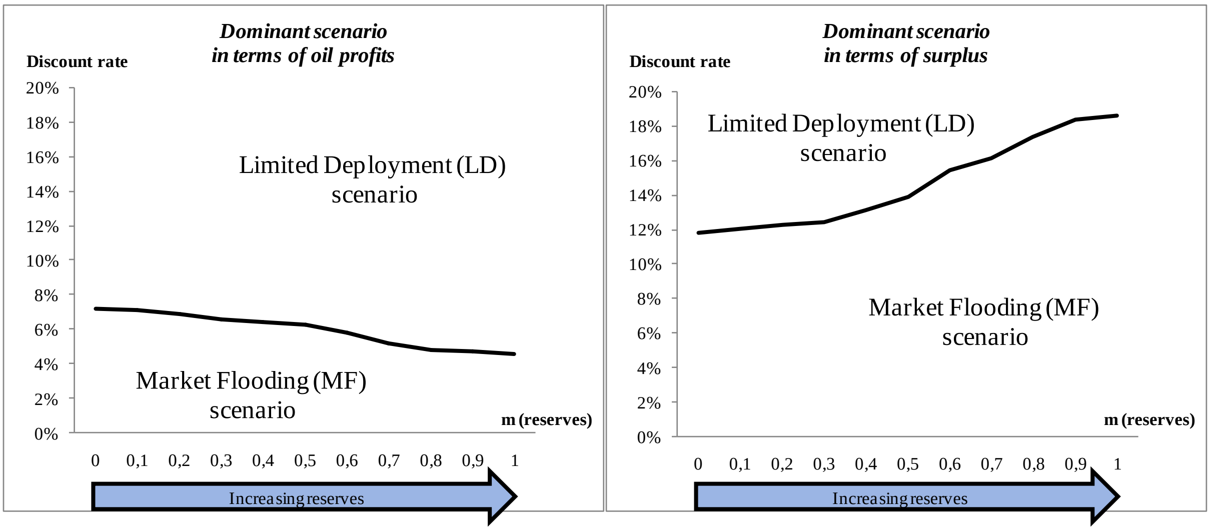
FIGURE 5. *Mean oil price during the post-Peak Oil period with respect to the amount of reserves and inertia on the deployment of non-conventional reserves*



3.3 Peak Oil and the strategic space of Middle-East producers

The above findings help delineate the strategic space for Middle-East countries, i.e. how the dominance of either polar strategy (MF vs LD) is determined by anticipation of ultimate resources and by the choice of discount rates. For a given scenario, higher reserves decrease discounted Middle-East oil revenues in all scenarios because later Peak Oil postpones the bubble of long-term oil revenues, and limits its magnitude due to lower long-term oil prices. The size of the reserves influences the trade-off for Middle-East producers between a MF- and a LD-strategy, and figure 6 displays the domains over which each strategy is dominant for the two decision criteria described in section 2.2.

FIGURE 6. *Dominant scenario for ME countries with respect to the amount of reserves and discount rate in terms of oil profits (left panel) and surplus (right panel).*



When producers act as purely private companies, the threshold value for discount rates remains low (5-7%) and the trade-off favors the LD scenario for all reserve assumptions (Figure 6, left panel). When considering social surplus, threshold discount rates are much higher and delineate a notably wider dominant space for the MF scenario (Figure 6, right panel).

More remarkably, for economically meaningful reasons, the trend of the curves with respect to the size of the reserves depends on the decision criterion. The downward oriented slope in (Figure 6, left panel) demonstrates that the MF scenario is penalized by high reserves with private assessments. Indeed, higher reserves lead to a longer period of technical change before constraints on oil supply appear, and economies are less oil-dependent when hit by

‘Peak Oil’. This leads to a delayed and lower long-term bubble of oil profits which affects the reward for the short-term sacrifice.

When considering social assessments instead, the upward oriented slope in (Figure 6, right panel) demonstrates that the MF scenario is favored by high reserves. This is due to the impact of oil reserves on the magnitude and timing of the ‘Dutch Disease’ mechanism. Higher reserves lead to a longer period during which oil importers are directed towards oil-intensive pathways. Middle-East countries then benefit from a higher reward for their short-term sacrifice. In contrast, higher reserves extend the period during which lower oil revenues in the MF scenario force the development of local industrial production in Middle-East countries which brings about an improvement of the long-run absorption capacity of the economy and proves beneficial for long-run activity.

4. Conclusion

In this paper, we review the notion of Peak Oil in a modeling framework that *(a)* describes oil markets in the face of inertia in the deployment of oil production capacity and technical change with non-perfect foresight, and *(b)* inserts this information into a general equilibrium analysis to investigate the economic effects of future oil markets on oil profits and economic activity. Peak Oil is not postulated but emerges endogenously as a result of market interactions. We find that the date of Peak Oil cannot go beyond 2040 unless very optimistic assumptions on oil reserves and/or pessimistic assumption about the recovery from the current economic crisis are considered.

The results for the macroeconomic consequences of Peak Oil in terms of rent formation are more robust to parameter uncertainty. We demonstrate that one key parameter of these consequences is the inertia limiting the short term adaptability of oil production. This inertia creates the possibility of a sudden acceleration in oil price increases if importing economies are very oil-dependent when entering the period of oil depletion.

The magnitude of the resulting macroeconomic impacts is significant enough to reassess the intertemporal tradeoffs of Middle-East producers. We demonstrate that, besides undermining oil exporters' revenues in the short term, low oil prices encourage intensive oil consumption, and accelerate the exhaustion of reserves. Oil-importing economies are then more oil-dependent at the Peak Oil date, and oil exporters experience a bubble of long-term profits. The overall effect leads to the counter-intuitive conclusion that it may be in the interests of oil producers to accept a temporary sacrifice in their short-term export revenues so as to benefit from higher long-term revenues in the post-Peak Oil period. But, given the time lag between this sacrifice and the bubble of long-term profits, they will do so only if they consider long-term macroeconomic objectives (including industrialization) instead of the maximization of discounted oil revenues.

Conversely, maintaining low energy prices makes the world economy more vulnerable to Peak Oil and may not ultimately be beneficial to oil importers. It may, on the contrary, be in their interest to correct those potentially misleading price-signals by using complementary measures (e.g., local fiscal policies, international climate policies) to secure steady technical change and to hedge against a negative long-term economic outcome. This possibility, in turn, raises the question of Middle-East countries' reaction to these measures which threaten their oil revenues.

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