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Peak Oil profiles through the lens of a general equilibrium assessment

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HIGHLIGHTS

- ▸ Geological determinants behind Hubbert curves in a general equilibrium framework.
- ▸ We endogenize the interactions between Peak Oil dates, oil prices and growth trends.
- ▸ Close Peak Oil dates lead to different trends of oil prices, exportation and growth.
- ▸ Low short-term prices benefit to the long-term macroeconomy of oil exporters.
- ▸ High short-term prices hedge oil importers against economic tensions after Peak Oil.

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ABSTRACT

This paper disentangles the interactions between oil production profiles, the dynamics of oil prices and growth trends. We do so through a general equilibrium model in which Peak Oil endogenously emerges from the interplay between the geological, technical, macroeconomic and geopolitical determinants of supply and demand under non-perfect expectations. We analyze the macroeconomic effects of oil production profiles and demonstrate that Peak Oil dates that differ only slightly may lead to very different time profiles of oil prices, exportation flows and economic activity. We investigate Middle-East's trade-off between different pricing trajectories in function of two alternative objectives (maximisation of oil revenues or households' welfare) and assess its impact on OECD growth trajectories. A sensitivity analysis highlights the respective roles of the amount of resources, inertia on the deployment of non conventional oil and short-term oil price dynamics on Peak Oil dates and long-term oil prices. It also examines the effects of these assumptions on OECD growth and Middle-East strategic tradeoffs.

0. Introduction

The public debates about the future of oil markets have been largely shaped by the so-called 'Peak Oil', which relays concerns about the consequences of the inexorable decline of world oil production. The analyses have been focused on the date of this Peak Oil and are essentially conducted under the assumption that, given exogenous assumptions on the total amount of oil resources, oil production levels at a given point in time are only determined by remaining reserves in the soil, in turn depending on the sum of past production (see (Al-Husseini, 2006) for a review). This vision is supported by the generalization, at a global level, of bell-shaped profiles used by Hubbert to predict the decline of US production in the 1970s ((Hubbert, 1956, 1962; Deffeyes, 2002). Note that these curves are meant to capture geological constraints in the form of depletion effects and inertias on the deployment of production capacities.

This paper starts from the idea that the date of Peak Oil is an effective warning about constraints on cheap oil as a crucial energy source (Reynolds, 1994), but distracts the attention from its core determinants and economic consequences. Setting aside controversies about the generalization at a macro level of the Hubbert approach (Lynch, 2003), this paper argues that what matters is not so much the date of Peak Oil than the abruptness of the unanticipated break in oil trends at that period and the capacity of the economies to adapt to it.

This abruptness and its economic consequences are determined by the relative evolution rates of oil supply, fuel demand and oil substitutes under imperfect expectations and inertia constraints. To investigate the interplay between these dimensions, we use a Computable General Equilibrium (CGE) model, which incorporates a comprehensive description of the determinants of oil markets,

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including the geological constraints behind the Hubbert curves. This framework pictures a world with imperfect foresight, endogenous technical change and inertia on the deployment of end-use equipments and oil substitutes. Section 1 describes and justifies this modeling option.

Section 2 conducts a comparative analysis of two oil pricing trajectories: high short-term prices caused by a limited deployment of production capacities *vs.* moderate short term prices caused by a market flooding behavior. The former allows high short-term revenues for oil-producing countries, while it limits the vulnerability of oil-importing economies to Peak Oil by accelerating oil-free technical change; the latter discourages oil-saving technical change and triggers high prices after the occurrence of Peak Oil. The economic consequences of these two scenarios are investigated from the point of view of both oil exporters (in terms of oil revenues and macroeconomic effects) and oil importers (as measured by growth trajectories).

Section 3 conducts a sensitivity analysis on the results by considering different assumptions regarding the amount of oil resources and the extent of inertias that characterize non-conventional production. We assess their impact on economic outcomes and show in particular the parameter sets under which the temporary sacrifice of short-term oil profits under the market flooding option may prove beneficial for Middle-East producers thanks to the later increase of their revenue.

1. Endogenizing Peak Oil in a second-best economy

Long run general equilibrium interactions between oil markets and economic growth are conventionally investigated either with models picturing exhaustible resource exploitation à la Hotelling (1931) (see Anderson (1972), Solow (1974) or Stiglitz (1974) and Krautkraemer (1998) for a review), or with energy-economy models which conventionally assume steady growth pathways and aggregate supply curves (IPCC, 2007). The first approach cannot but conclude, instead of a Peak Oil, to a steady decline of production over time because they use an intertemporal optimization framework which confronts the "catch-22" syndrome[1]: "you need future information – what you will discover – to optimally control discovery in the present, but you cannot know future information until *after* you explore in the present, and thus you cannot optimally control your current exploration and production in a Hotelling principle sense" (Reynolds and Baek, 2012). The second approach, meant to explore long run pathways, neglects the importance of geological constraints on short term adaptability of oil production because oil demand, driven by steady growth, evolves smoothly.

The short-term consequences on the economy are only considered in two independent traditions. On the one hand, econometric analyses developed after the oil shocks investigate the transmission channels between oil prices and GDP but do not account for long term resource depletion because of their short-term focus (Hamilton, 2008). These studies demonstrate that modeling exercises can better reproduce the observed magnitude of the economic effect of oil price variations if they include (1) *mark-up pricing* to capture market imperfections (Rotemberg and Woodford, 1996); (2) *partial utilization rate of capital* when the full utilization of installed production capacities cannot be achieved due to limits in the substitution between capital and energy (Finn, 2000); (3) *a putty-clay description of technologies* to represent the inertias in the renewal of capital stock (Atkeson and Kehoe, 1999); (4) *frictions in the reallocation of capital across heterogeneous sectors* causing differentiated levels of idle production capacities (Bresnahan and Ramey, 1993); (5) *frictions in the reallocation of labor across heterogeneous sectors* causing differentiated levels of unemployment (Davis and Haltiwanger, 2001). On the other hand, recursive partial equilibrium analyses of supply/demand adjustments can predict Peak Oil if they take into account the information and depletion effects at the origin of the small-large-small sequence of discoveries (Reynolds, 1999a). This group of studies teaches us the crucial role played by geological constraints, geopolitical dimensions, technical inertias and imperfect foresight on short-run oil supply adaptability (Reynolds, 2009). But, these approaches fail to consider macroeconomic impacts of Peak Oil (see Fattouh, 2007 for a review).The purpose of this paper is thus to embark them in such a geological-based analysis. This is done using the CGE model Imaclim-R, which captures the general equilibrium effects of short-term dynamics in second-best economies at different time horizons.

1.1. Modeling the impact of oil markets on macroeconomic dynamics

Imaclim-R (Waisman et al, 2012) is a recursive CGE model of the world economy, divided in 12 regions[2] and 12 sectors[3]. It is calibrated for the 2001 base year by modifying the set of balanced input–output tables provided by the GTAP-6 dataset (Dimaranan, 2006) to make them fully compatible with 2001 IEA energy balances (in Mtoe) and data on passengers' mobility (in passenger-km) from (Schäfer and Victor, 2000). The model was tested against historic data up to 2006 (Guivarch et al., 2009) and covers the period 2001–2050 in yearly steps through the recursive succession of static equilibria and dynamic modules. It incorporates the above listed five features identified from econometric analyses as crucial for the representation of energy-economy interactions.

The *static equilibrium* represents short-run macroeconomic interactions at each date *t* under technology and capacity constraints. It is calculated assuming Leontief production functions with fixed intermediate consumption and labor inputs, decreasing static returns caused by higher labor costs at high utilization rate of production capacities (Corrado and Mattey, 1997) and fixed mark-up in non-energy sectors (feature 1). Households maximize their utility through a tradeoff between consumption goods, mobility services and residential energy uses considering fixed end-use equipments. Market clearing conditions can lead to a partial utilization of production capacities (feature 2) given the fixed mark-up pricing and the stickiness of labor markets (feature 5). This equilibrium provides a snapshot of the economy at date *t* in terms of relative prices, wages, employment, production levels and trade flows.

The *dynamic modules* are reduced forms of bottom-up models, which describe the evolution of structural and technical parameters between *t* and $t+1$ in response to past and current economic signals. Available techniques at date *t* result from the structure and amount of cumulated learning-by-doing processes within the innovation possibility frontier characterizing explicitly the ultimate potentials on the supply and demand side (Ahmad, 1966). Technical choices modify only new input–output coefficients

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[1] A notable exception is in Holland (2008) who obtains a peak of production in an Hotelling-like framework by embarking forces that increase the equilibrium production and counterbalance the decreasing trend imposed by the depletion effect.

[2] USA, Canada, Europe, OECD Pacific, Former Soviet Union, China, India, Brazil, Middle-East, Africa, rest of Asia, Rest of Latin America.

[3] Three primary energy sectors (Coal, Oil, Gas), two transformed energy sectors (Liquid fuels, Electricity), three transport sectors (Air, Water, Terrestrial Public Transport) and four productive sectors (Construction, Agriculture, Industry, Services).

and not those of techniques embodied in equipments resulting from past choices. This putty-clay description helps to capture inertias on the renewal of technologies (feature 3) and capital (feature 4). Note that this description of inertia also enables a realistic reproduction of the heterogeneity in technical dynamics across regions. The new technical coefficients and investment choices are sent back to the static module in the form of updated input–output coefficients and production capacities to calculate the equilibrium at date $t+1$.

The consistency of the iteration between the static equilibrium and dynamic modules relies on 'hybrid matrices' (Hourcade et al., 2006), which ensure a description of the economy in consistent money values and physical quantities (Sands et al., 2005). This dual description represents the material and technical content of production processes and allows abandoning standard aggregate production functions, which have intrinsic limitations in case of large departures from the reference equilibrium (Frondel and Schmidt, 2002) and deep changes of production frontiers over several decades.

In this multisectoral framework with partial use of production factors, effective growth patterns depart from the natural rate (Phelps, 1961) given by exogenous assumptions on active population (derived from UN medium scenarios) and labor productivity (satisfying a convergence hypothesis (Barro and Sala-i-Martin, 1992) informed by historic trajectories (Maddison, 1995) and 'best guess' assumptions (Oliveira Martins et al., 2005). The structure and rate of effective growth at each point in time are endogenously determined by (a) the allocation of the labor force across sectors, which is governed by the final demand addressed to these sectors (b) the sectoral productivities which result from past investment decisions governing learning by doing processes (c) the shortage or excess of productive capacities which result from past investment decisions under adaptive expectations.

1.2. *Modeling the long-term dynamics of oil markets*

The determinants of oil markets are described in dynamic modules which include lessons from partial equilibrium analyses of supply/demand adjustments on oil markets. They represent: the technical constraints (including geology) on the short-term adaptability of oil supply and the influence of Middle-East countries on production decisions (Section 1.2.1); technical inertias on the deployment of oil substitutes (1.2.2); and consumers' short-term trade-offs in a set of technical and economic conditions (1.2.3).

1.2.1. *Oil supply*

Imaclim-R distinguishes seven categories of conventional and five categories of non-conventional oil resources in each region. Each category i is characterized by the amount of ultimate resources $Q_{\infty,i}$ (given by the sum of resources extracted before 2001 and recoverable resources) and by a threshold selling price above which producers initiate production, $p^{(0)}(i)$. This price is a proxy for production costs and accessibility. Table 1 gives our numerical assumptions of the amount of ultimate resources in the main groups of regions. The figures are consistent with conservative estimates (USGS, 2000; Greene et al., 2006; Rogner, 1997) and a sensitivity analysis in Section 3 will investigate the effect of more pessimistic or optimistic assumptions. Note that oil shales are not included because the specificities of their exploitation process and the associated high production cost lead us to consider them as an alternative to oil instead of a new category of oil.

Table 1
Assumptions about oil resources in the central case (Trillion bbl).

Resources extracted before 2001	**Recoverable resources beyond 2001**[a]				
	Conventional oil		Non-conventional oil (heavy oil and tar sands)		
	Middle-East	RoW	Canada	Latin America	RoW
0.895	0.78	1.17	0.220	0.38	0.4

[a] "Recoverable resources" are 2P reserves (proven+probable) remaining in the soil, which has been identified as the relevant indicator to investigate global oil peak (Bentley et al., 2007).

Each oil category is submitted to geological constraints (inertias in the exploration process and depletion effects), which limit the pace of expansion of their production capacity. In line with (Rehrl and Friedrich, 2006), who combine analyzes of discovery processes (Uhler, 1976) and of the "mineral economy" (Reynolds, 1999a), the inelasticity of oil supply is represented by imposing a maximum rate of increase in production capacity for an oil category i at date t, $\Delta Cap_{\max}(t,i)$, as given by:

$$\frac{\Delta Cap_{\max}(t,i)}{Cap(t,i)} = \frac{b_i \times (e^{-b_i(t-t_{0,i})}-1)}{(1+e^{-b_i(t-t_{0,i})})} \tag{1}$$

The parameter b_i (in t^{-1}) controls the intensity of constraints on production growth: a small (high) b_i means a flat (sloping) production profile to represent slow (fast) deployment of production capacities. We retain $b_i=0.06$/year for conventional oil as estimated by Rehrl and Friedrich (2006) and, for the sake of simplicity, the same value for non-conventional oil in the median case (Section 3 relaxes this hypothesis by considering both lower and higher values of the b-parameter for non conventional oil). The parameter $t_{0,i}$ represents the date at which production capacities of the concerned oil category are expected to start to decline due to depletion effects. It is endogenous and varies in time since it depends on the amount of oil remaining in the soil given past exploitation decisions.

Non-Middle-East producers are seen as 'fatal producers' who do not act strategically on oil markets. Given the selling oil price p_{oil}, they invest in new production capacity if an oil category becomes profitable: they develop production capacities at their maximum rate of increase $\Delta Cap_{\max}(t,i)$ for least-cost categories ($p_{oil} > p^{(0)}(i)$) but stop investments in high-cost categories ($p_{oil} < p^{(0)}(i)$). If prices continuously increase, production capacities of a given oil category follow a bell-shape trend, whereas their deployment profile passes through a plateau if prices decrease below the profitability threshold.

Middle-East producers are 'swing producers' who are free to strategically time their investment decisions (in particular, they can decide unilaterally to reduce their output) and, who, until they reach their depletion constraints, control oil prices through the utilization rate of their production capacities (Kaufmann et al, 2004). This possibility is justified by the temporary reinforcement of their market power due to the stagnation and decline of conventional oil in the rest of the world. They can in particular decide to slow the development of production capacities below its maximum rate in order to adjust the oil price according to their rent-seeking objective.

Total production capacity at date t is given by the sum over oil categories of investment decisions which are conditioned by different production costs (captured by different $p^{(0)}(i)$ threshold). This means that projects of various merit orders coexist at a given point in time, consistently with the observed evidence and theoretical justifications[4] .

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[4] Kemp and Van Long (1980) have indeed demonstrated that, in a general equilibrium context, the lowest-cost deposits are not necessarily exploited first.

1.2.2. Substitutes to oil for liquid fuels production

The first large-scale substitute to oil for liquid fuels production consists in first and second generation biofuels from renewable land resources. Their diffusion is controlled by supply curves borrowed from IEA (2006): at each date, biofuels' market share is an increasing function of oil prices which captures in a simplistic manner the competition between biofuels and oil-based liquid fuels (everything else being equal, the former are more competitive and their penetration into the market is more prominent when higher oil price make the latter more expensive). These supply curves consider explicit limits on production due to land availability and competition with other biomass uses and are modified from one date to the other to account for learning-by-doing improvements.

The second alternative to oil is Coal-To-Liquid (CTL). We consider it as an inexhaustible backstop technology submitted to deployment capacity constraints. In line with Amigues et al. (1998), production of the inexhaustible substitute starts before all the least-cost deposits of the exhaustible resource are exploited: CTL enters the market when oil prices exceed a threshold value, p_{CTL}, set for the sake of simplicity at $p_{CTL}=100\$/\mathrm{bbl}$ for all scenarios.[5] Once this threshold is crossed, 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), $S(t)$. But, CTL production may be limited by constraints on delivery capacity due to past investment decisions if, due to imperfect foresight, profitability prospects for CTL were underestimated. These prospects are an increasing function of oil prices at each point in time[6] and cumulative investment on CTL over time is then a function of the sum of past oil prices: $p_{cum}(t)=\Sigma_{i=2010}^{t}p_{oil}(i)$. The share s of the potential market for CTL $D(t)-S(t)$ that is actually available to CTL is thus an increasing function of $p_{cum}(t)$. As soon as oil price exceeds p_{CTL}, CTL production is then given by:

$$CTL(t)=s(p_{cum}(t)).[D(t)-S(t)] \tag{2}$$

1.2.3. Liquid fuels' demand

In IMACLIM-R, final demand for liquid fuels is not represented with rather abstract elasticities but with explicit households' and industry's demand for energy services, derived from utility and profit maximization under technological constraints, respectively. Bottom-up modules describe the dynamics of technological constraints in the three major oil-consuming sectors (industry, residential, transport) and are described in full details in the Supplementary Material of (Waisman et al., 2012). Because of inertias in the renewal of end-use equipment and the pace of learning-by-doing processes, 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 under imperfect foresight. In the transport sector, passengers' mobility and modal distribution depend on (i) households' choices from an explicit portfolio of vehicles (including electric vehicles) according to minimization of the total user-costs (which depend *inter alia*, on relative energy prices) and (ii) the availability and efficiency (including congestion effects) of road infrastructures and alternative options (railways, soft modes) driving the saturation of the time budget the consumer can allocate to transportation. In the long-run, the decoupling between liquid fuel demand and economic growth is constrained by (i) higher energy service demand (mobility, residential uses) along with wealth increase (ii) technical asymptotes for fuel switching and energy efficiency, (iii) limited potentials for non-fossil energies including political obstacles for nuclear (iv) increasing trends in freight mobility imposed by international trade and just-in-time processes (v) rebound effects in passenger mobility (Greening et al., 2000).

2. Peak Oil profiles and their macroeconomic dimensions

In this section, we study the implications of two oil pricing trajectories resulting from alternative strategic options for Middle-East producers under the same assumptions on the determinants of liquid fuel demand.[7] We define two counterfactual scenarios having the same amount of reserves but differing in terms of oil investment dynamics[8]:

- *The Market Flooding scenario* (*MF*): Middle-East producers expand their production capacities and bring the oil price back to its pre-2004 level, $p_{low}=50\$/\mathrm{bbl}$. This floor level is assumed to be sufficient to maintain the stability in the cartel and guarantees a minimum level of income to highly populated countries.
- *The Limited Deployment scenario* (*LD*): Middle-East producers refrain from investing in new capacity and maintain the medium term oil price around $p_{high}=80\$/\mathrm{bbl}$. They adopt local fiscal policies to secure domestic social stability by moderating the increase of energy prices for the consumers of the region.[9]

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 Market Flooding scenario and in 2028 in the Low Deployment scenario (Fig. 1). In the Market Flooding scenario, oil-intensive growth patterns are fostered by low prices which accelerate the exhaustion of conventional resources and leads to an early Peak Oil. This corresponds to a pronounced bell-shaped profile with significant break in production trends at the Peak Oil date and fast decrease after that. In the Low Deployment scenario, on the contrary, higher short-term prices foster moderation of demand and lead to a flatter profile, in the form of a plateau; the reversal of production trends at the end of this plateau is smooth and production volumes decrease at a moderate pace in the long term. Total supply even becomes higher than in the Market Flooding case after 2040.

(*footnote continued*)
Holland (2003) even demonstrates that least-cost-first extraction rule does not hold in partial equilibrium under capacity constraints, like those envisaged for geological reasons here.

[5] This 100$/bbl threshold is quite high compared to existing assessments of current profitability thresholds for CTL, because of entropy subsidy issues (Reynolds, 1999b) according to which the cost of all energies increases when oil prices go up (including coal used as the primary energy used for CTL production).

[6] Indeed, higher oil prices drive higher prices of liquid fuels, including those produced from coal, and then higher profitability prospects for CTL.

[7] These scenarios are built on a single set of assumptions about natural growth rates, which intentionally do not represent the current economic crisis for the sake of simplicity. But, the analysis carried out in this paper provides important insights on the medium term dynamics of the economic recovery phase, which will be critically determined by the economic interactions on oil markets. Further investigation will be necessary to consider the feedback effect of the current economic crisis on the real behaviors of oil markets, specifically because of the inertia of re-launching investments in both conventional and non conventional oil.

[8] By doing so, we neglect the effect of oil investments dynamics on the rate of technological progress although it affects the amount of ultimately recoverable reserves, like for example the risk of reserve reduction if Middle-East producers do not follow a smooth path of production. (see discussion in Reynolds and Kolodziej (2009).

[9] The values of p_{low} and p_{high} are expressed in 2001$ and correspond respectively to around 60$/bbl and 100$/bbl in current currency. They represent a low and high value for medium-term oil price, around the estimate of 78$/bbl by the short-term energy outlook 2010 (available at: http://www.eia.doe.gov/emeu/steo/pub/contents.html).

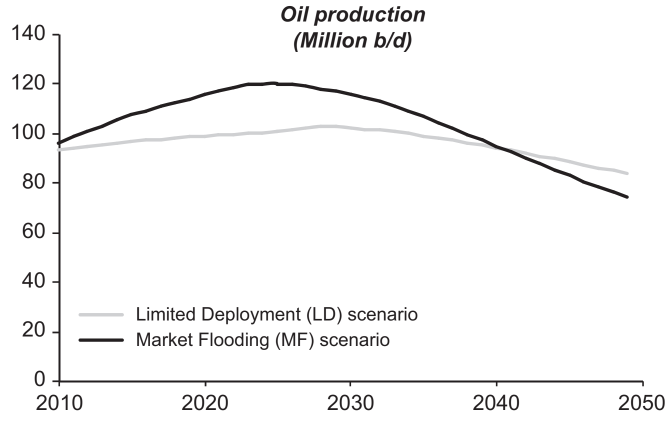

Fig. 1. World oil production (Million b/d).

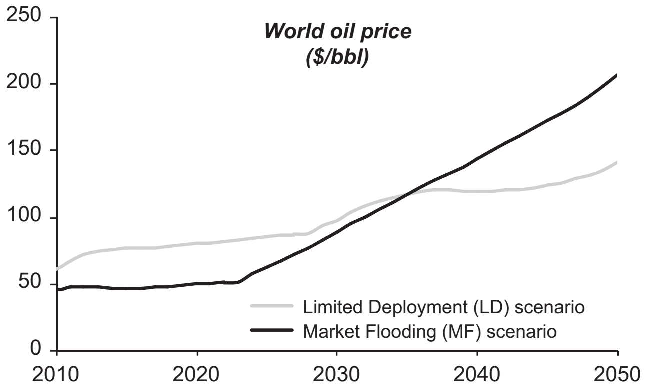

Fig. 2. World oil price ($/bbl).

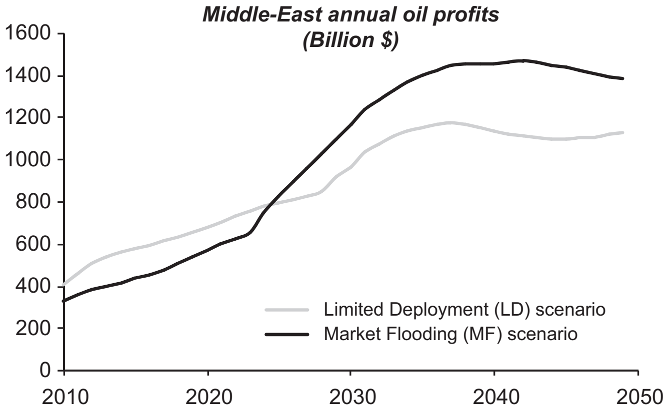

Fig. 3. Middle-East annual oil profits (Billion$).

The small gap in the Peak Oil dates masks indeed important differences in the production profile. The peak level is 20% higher in volume in the Market Flooding scenario (120 Million b/d) and the reversal of production trends after the Peak Oil is more abrupt (the production declines by 31% in the Market Flooding scenario and only 17% in the Low Deployment scenario over the twenty years following Peak Oil). Logically indeed, lower energy prices in the first period (a) induce intensive consumption causing faster exhaustion and sharper decline of conventional oil, and (b) deter investment in non-conventional production capacities and limit their availability in the post-Peak Oil period.

In the Market Flooding scenario, a steep and lasting surge in oil prices begins just before Peak Oil (Fig. 2). It is triggered by tension between high demand, which cannot be reduced overnight due to inertias, and the constraints on the deployment of oil and oil substitutes' production capacities. Conversely, prices in the Low Deployment scenario increase smoothly and are lower than prices in the Market Flooding scenario after 2035, because high early price signals foster a timely penetration of oil substitutes and trigger energy efficiency abroad (Fig. 2). Over the very long run, oil prices return to the price of the backstop CTL (100$/b) in both scenarios, but inertias in the penetration of this technology prevent this convergence during the period 2010–2050 considered in this paper.

2.2. *The terms of the economic trade-off for oil producers*

The time-profile of Middle-East oil profits (Fig. 3) results from the volume and price effects described in Section 2.1. Short-term oil revenues are higher under the Low Deployment scenario than in the Market Flooding scenario, but the situation is reversed after Peak Oil. In both scenarios, the post-Peak Oil rise of oil prices induces a surge of oil revenues; this surge is amplified in the Market Flooding scenario because of higher long-term oil prices. In this scenario, Middle-East countries can thus expect a reward for sacrificing short-term revenues and the trade-off between these two strategies depends on the objective function of Middle-East countries. Let us consider two polar objective functions as extreme cases where they put all weight on private interests (by maximizing oil revenues) or on the public welfare (by maximizing domestic households' surplus).

In the first case, Middle-East oil companies act as profit maximizing firms independent from any political influence. They choose their strategy based on discounted cumulated oil revenues and adopt the Market Flooding option only for discount rates lower than 6% (Table 2). This 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[10]). Even though the recent financial crisis casts doubts upon the persistence of so high a profitability ratio, a breakeven point as low as 6% suggests that the adoption of the Market Flooding scenario is unlikely under this decision criterion (see Adelman, 1986 for a more detailed analysis of discounting in the specific case of major oil producing countries).

Table 2
Middle-East's discounted oil profits (Billion $).

Discount rate (%)[a]	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

[a] We present results for a selection of discount rates around the threshold values 5–6% defining the range of interest for the analysis.

Let us now assume that Middle-Eastern companies are managed in function of long-term public objectives. This means that Middle-East countries impose upon oil companies and sovereign funds to adopt pricing and investment decisions that maximize their households' surplus and to compare the general equilibrium

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[10] Determination of 2002 discount rate range for petroleum and hard mineral (available at: http://www.window.state.tx.us/taxinfo/proptax/drs02/).

effects of the two pricing strategies. Table 3 reports the variation of the population's surplus ΔS between the two scenarios: $\Delta S = \Delta R - CVI$, where ΔR and CVI are the effective and compensative variation of income, respectively, the latter measuring the amount of income that would leave utility unchanged, given changes in relative prices. With this criterion, the Market Flooding scenario becomes a workable alternative because the social discount rate is lower than the private one, and because the range of discount rates for which the Market Flooding scenario is desirable proves to be much wider than with the oil profit maximization criterion: [0%−13%]instead of [0%−7%].

The difference between the two results originates in the long term macroeconomic effects of the two investment strategies. For a given assumption about the balance of payments, high short-term oil export revenues in the Low Deployment scenario are consistent with higher imports of industrial goods and a higher exchange rate of local currencies. This penalizes local industry and slows the transition of Middle-East countries away from oil-based revenues towards industrialization. Conversely, in the Market Flooding scenario, lower oil revenues allow for lower exchange rates. The development of local industry partially offsets short-term losses in oil revenues and better prepares Middle-East countries for the post oil era. 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 benefit to a more mature industrial structure. This captures in a simple form the'natural resource curse' (Sachs and Warner, 2001) and the 'Dutch Disease': high resource rents do not guarantee sustainable growth patterns if limits in the absorption capacity of the economy weaken efficient re-investment in non-rent production sectors.

2.3. The adverse effects of cheap oil in oil-importing countries

Over the 2010–2050 time period, average GDP growth rates in the OECD are estimated to be 1.57% in the Low Deployment scenario vs. 1.53% in the Market Flooding scenario. These differences appear to be small in terms of discounted consumption (0.92% with a 2% pure time preference) or when translated into a growth delay (13 months). However, these aggregate indicators hide more significant discrepancies in the time profile of economic growth in OECD (Table 4).

Table 3
Difference in households' surplus in the LD scenario with respect to the MF scenario (Billion $).

Discount rate (%)[a]	Discounted surplus in LD w.r.t. MF
5	−1862
10	−251
13	−30
14	+3
15	+26
20	+58

[a] We present results for a selection of discount rates around the threshold values 13–14% defining the range of interest for the analysis.

An interesting indicator to investigate the importance of these time dependencies is the difference between natural and effective growth at different time horizons. Indeed, when effective growth is lower than (or very close to) the natural rate, it is impossible to avoid tensions in sectors or regions that are below this average effective growth, and to absorb the total labor force at constant wages. This happens in particular when investment and technical constraints inhibit the reallocation of the labor force towards the more productive sectors. Table 4 shows that the effective growth exceeds natural growth over the whole "pre-Peak Oil period" in the Market Flooding scenario and logically allows for higher OECD growth rates due to cheaper oil imports and cheaper energy for households and enterprises. During the "Peak Oil period", the slowing down of economic growth starts sooner in the Market Flooding scenario and is more intense because Peak Oil hurts a more oil-dependent economy. During that period, the effective growth rate falls below the natural one for 10 years (2030–2040) in the Market Flooding scenario and continues to do so between 2040 and 2047. This corresponds to periods with high risks of social tensions. This situation never happens in the Low Deployment scenario.

These results lead to the conclusion that low energy prices over the short term are not necessarily beneficial for oil-importing countries since they may trap them in an oil dependency causing a strong variability of economic activity and lasting economic stagnation around and after the Peak Oil.

3. Uncertainties and their economic implications

After focusing on median assumptions for major determinants of oil markets, let us now conduct a sensitivity analysis to show the linkages between the main economic indicators and alternative assumptions on:

- the regional and total amount of oil resources; given controversies between pessimistic and optimistic views about these resources, we test a number of alternative scenarios in which the amount of resources is a weighted average between two extremes: 3.5 Trillion (10^{12}) bbl as a higher bound (2.3 Trillion bbl remaining conventional and 1.2 Trillion bbl of non conventional resource, in line with IEA (2008) estimates which gives a range for non conventional resources from 1 to 2 Trillion bbl) and 2.4 Trillion bbl as a lower bound (1.6 Trillion bbl conventional and 0.8 Trillion bbl of non conventional), in line with estimates from the Association for the Study of Peak Oil (ASPO). 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 uncertainties on the rate of deployment of non-conventional oil: 0.07; 0.06 (value used in Section 2); 0.05, and 0.04. A higher b-value means an easier exploitation and faster deployment of non-conventional resources.

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

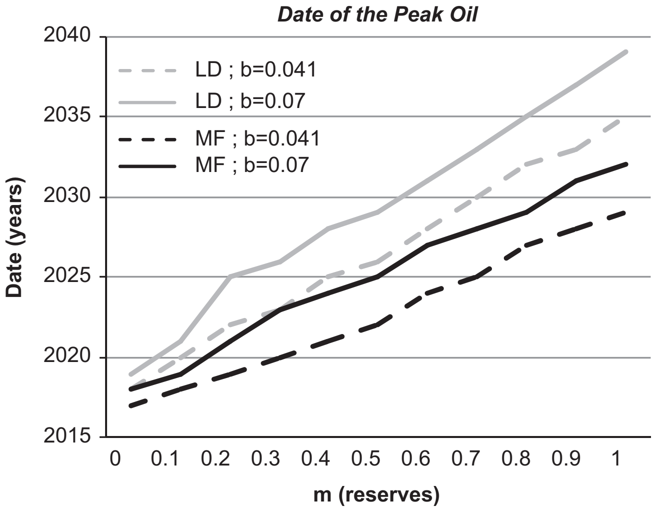

Fig. 4. Sensitivity of the date of Peak Oil with respect to the amount of resources and inertia in the deployment of non-conventional oil.

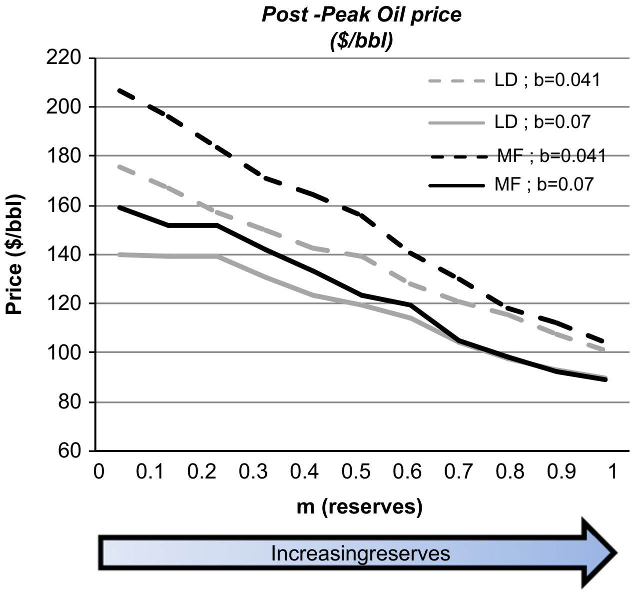

Fig. 5. Mean oil price during the post-Peak Oil period with respect to the amount of resources and inertia on the deployment of non-conventional oil.

3.1. *Early or late 'Peak Oil'? Geological uncertainties matter more that OPEC strategies*

Fig. 4 demonstrates a wide range of Peak Oil dates, from 2017 to 2039. Unsurprisingly, the size of the ultimate oil resource is the major determinant of this 22 year range, as shown by the strong increase of all curves from left to right. This figure also confirms the diagnosis of the median case analysis: for moderate assumptions on oil reserves, Peak Oil dates are weakly sensitive to the short-term price trajectory (the difference between Market Flooding and Low Deployment scenarios does not exceed five years for $m < 0.5$).

In contrast, in case of abundant reserves, the sensitivity analysis demonstrates that the Peak Oil date depends significantly on other determinants. With $m=1$, the Peak Oil date varies by 11 years with respect to the selected pricing trajectory and technical parameters on non-conventional oil. This represents half the range of variations in Peak Oil dates and confirms a basic intuition of the paper, namely that, although the amount of reserves is an important factor, other economic and technical parameters may also play a key role in the determination of Peak Oil date.

3.2. *Long-term oil prices after Peak Oil*

We now investigate the sensitivity of the average value of oil prices in the post-Peak Oil period, which is an indicator of tensions on oil markets (Fig. 5). First, higher ultimate resources result in lower long-term oil prices as captured by the decreasing trend of all cruves from left to right. Indeed, *ceteris paribus*, higher resource gives a longer period for deploying oil-saving technologies and makes the economy less oil-dependent after Peak Oil. Second, long-term prices are always higher under a Market Flooding scenario because, misled by low price signals, oil-importing economies adopt more oil dependent consumption patterns triggering high demand. Third, optimistic views on non-conventional oil logically favor lower long-term prices by allowing a timely diffusion of substitutes to conventional oil, and hence helping to reduce the supply-side constraints on oil markets.

Interestingly, the comparison of sensitivity tests in 3.1 and 3.2 confirms that the date of Peak Oil says nothing about the time profile of oil prices. Indeed, in low resource cases, the date of Peak Oil is almost independent of parametric assumptions on pricing trajectories and inertias on the deployment of non-conventional oil, but these assumptions have a strong influence on long-term oil prices because they determine the abruptness of the break in demand and supply trends. Conversely, under high reserves, the wide range of Peak Oil dates hardly affects long-term oil prices, which remain moderate in all cases; indeed, Peak Oil happens late (not before 2028 under the more optimistic reserve assumption) so that oil-free technical change and the diffusion of substitutes to conventional oil have sufficiently progressed to limit the abruptness of the break in production and consumption trends at the Peak Oil period.

3.3. *Macroeconomic effects and oil uncertainties*

The analysis in Fig. 6 shows that, unsurprisingly, more abundant reserves foster faster OECD growth by offering more abundant resource to these oil-importing economies. It also confirms for all parametric assumption that the Low Deployment scenarios are more profitable for OECD economies as they reduce their vulnerability to Peak Oil. On average this benefit is small and rather insensitive to parametric assumptions (less than 0.1% difference between the more extreme cases).

However, like in the median case, a much more contrasted picture is obtained when considering the time profiles. In particular, with low reserves, strong inertias on the deployment of non conventional oil and low short term oil prices, economic growth remains quite below the natural growth rate during 25 years after Peak Oil (Table 5), which is indicative of long lasting economic tensions.

The situation is different for oil exporters, which appear more sensitive to parametric assumptions even for aggregate indicators like discounted revenues and discounted economic activity. We analyze these effects by delineating the domains of discount rates and resources over which each pricing scenario is dominant for Middle-East producers under the two decision criteria described in Section 2.2 (Fig. 7).

In all scenarios, higher resources decrease discounted Middle-East oil revenues, since later Peak Oil postpones the long-term rise of oil revenues consecutive to Peak Oil and limits its magnitude due to lower long-term oil prices. The magnitude of this effect depends on the scenario considered whilst the amount of reserves also influences Middle-East producers' trade-off between the MF and Low Deployment scenarios.

When producers act as private companies, the threshold value for discount rates remains low (5–7%) and the trade-off favors the Low Deployment scenario for all assumptions (Fig. 7, left panel). When considering social surplus, threshold discount rates are much higher and delineate a notably wider dominant domain for the Market Flooding scenario (Fig. 7, right panel).

More remarkably, for economically meaningful reasons, the trend of the curves with respect to the amount of resources depends on the decision criterion. The downward oriented slope in (Fig. 7, left panel) demonstrates that the Market Flooding scenario is penalized by high resources with private assessments. Indeed, higher resources lead to a longer period of technical change before constraints on oil supply appear, and oil-importing economies are less oil-dependent when hit by 'Peak Oil'. This leads to a delayed and lower long-term rise of oil profits which affects the reward for the short-term sacrifice.

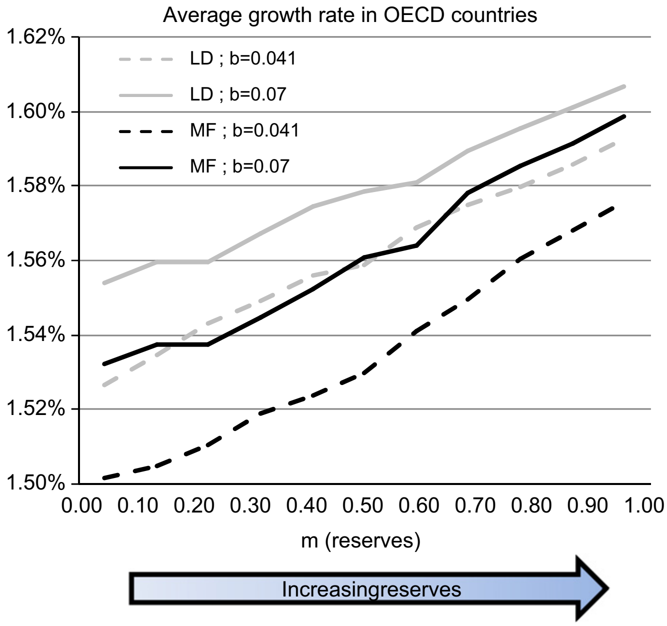

Fig. 6. Average growth rate in OECD countries with respect to the amount of resources and inertia on the deployment of non-conventional oil.

When considering social assessments instead, the upward oriented slope in (Fig. 7, right panel) demonstrates that the Market Flooding scenario is favored by high resources. This is due to the impact of oil resources on the magnitude and duration of the *Dutch Disease* mechanism and on the length of the period during which oil importers are directed towards oil-intensive pathways. Higher resources extend the period during which lower oil revenues in the Market Flooding scenario force the development of local industrial production in Middle-East countries. In this way, the long-run absorption capacity of Middle-East economies is improved after Peak Oil, i.e., at the moment when they get the more important revenues from oil exportations.

4. Conclusion

This paper reviews the notion of Peak Oil in a general equilibrium modeling framework that represents the limits on the short term adaptability of oil supply, oil substitutes and fuel demand. In this framework, inertia and imperfect foresight create the possibility of a sudden acceleration in oil price increases if importing economies are very oil-dependent when entering the period of oil depletion.

By considering two counterfactual scenarios, sensitivity tests show that the date of Peak Oil is sensitive to short-term oil price only in case of high reserves and that Peak Oil dates that differ only slightly may lead to very different time profiles of oil prices, rent formation and growth patterns.

Table 5
Sensitivity tests on the time profile of OECD growth rates (%).

	Short-term period (2010–2025) (%)	Peak Oil period (2025–2040) (%)	Long-term period (2040–2050) (%)
Natural growth rates	1.69	1.30	1.19
Effective growth rates			
Minimum	1.85	1.19	1.10
Maximum	2.05	1.48	1.26

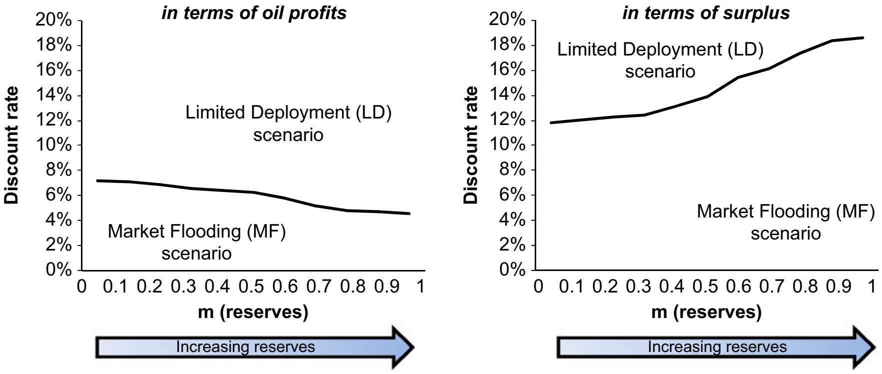

Fig. 7. Dominant scenario for Middle-East countries with respect to the amount of resources and discount rate in terms of oil profits (left panel) and surplus (right panel).

From oil exporters' point of view, low oil prices undermine short-term exportation revenues; but they encourage oil consumption, make oil-importing economies more oil-dependent at the Peak Oil date and create room for a rise of long-term oil exportation revenues. It thus 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, they will do so only if they consider long-term macroeconomic objectives (including industrialization and hedging against Dutch Disease) instead of the maximization of discounted oil revenues. This option is all the more attractive in case of high reserves.

From oil importers' point of view, long periods of low energy prices make the economy more vulnerable to Peak Oil and may not ultimately be beneficial. It may thus be in their interest to correct potentially misleading price-signals by using complementary measures to secure steady technical change. Among them, international climate policies can be envisaged as a hedging strategy against the negative long-term economic outcome of the uncertainty on oil markets (Rozenberg et al., 2010). Indeed, the moderation of short-term oil demand caused by carbon pricing may contribute to anticipate the long-run depletion and make the economy less sensitive to the rarefaction of oil. This possibility, in turn, raises the question of Middle-East countries' reaction to these measures and in particular their compliance to a global climate agreement, given the adverse impacts of climate policies on their oil exportation revenues. Our paper suggests that examining this question in a partial equilibrium approach or through the lens of a general equilibrium analysis may make a significant difference. To treat these questions, a new step in methodological advancements is necessary to introduce climate policies at the heart of the framework of energy-economy interactions developed in this paper.

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