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Worldwide cheap and heavy oil productions: A long-term energy model ☆

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ABSTRACT

Crude oil, natural gas liquids, heavy oils, deepwater oils, and polar oils are non-renewable energy resources with increasing extraction costs. Two major definitions emerge: regular or 'cheap' oil and non-conventional or 'heavy' oil. Peaking time in conventional oil production has been a recent focus of debate. For two decades, non-conventional oils have been mixed with regular crude oil. Peaking time estimation and the rate at which production may be expected to decline, following the peak, are more difficult to determine. We propose a two-wave model for world oil production pattern and forecasting, based on the diffusion of innovation theories: a sequential multi-Bass model. Historical well-known shocks are confirmed, and new peaking times for crude oil and mixed oil are determined with corresponding depletion rates. In the final section, possible ties between the dynamics of oil extraction and refining capacities are discussed as a predictive symptom of an imminent mixed oil peak in 2016.

1. Introduction and a review

Oil is a non-renewable resource formed in the geological past, in a process that took millions of years. It is not a homogeneous resource and, for this reason, we face different classification systems adopted by the Energy Information Administration (EIA), International Energy Agency (IEA), Oil and Gas Journal (OGJ), World Oil Magazine (WOm), British Petroleum Statistical Review of World Energy (BP), World Oil and Gas Review (WOeni), etc. Two major definitions emerge: regular or 'cheap' oil and non-conventional or "heavy" oil. The former refers to light and sweet crude oils, while the latter brings together different resources: natural gas liquids (NGL), heavy oils like tar sands and oil shales, deepwater oils, and polar oils, all of which incur increasing costs. The contribution of non-conventional oil in supplying the economy was very limited between 1900 and the 1970s. See, for instance, Campbell and Laherrère (1998). Campbell argues an asymptotic scenario with a non-conventional oil share around one-fifth.

Recent advances in producing and measuring techniques such as Q-technologies, new streamer technologies, periscope drilling, seismic-guided drilling, and deepwater technologies by Schlumberger (see Gould, 2009), constitute a strong example of the effort spent in order to overcome today's recession in the non-renewable energy area, the actual technological driver of worldwide economy. The *Deepwater Horizon* accident in 2010 is a paradigmatic example of the increasing risks and related direct and indirect costs in non-conventional situations.

Production at given oilfields is determined by common stimuli, such as transport costs, regulatory pressures, nearby markets, etc. Measuring oil in the ground is a difficult task because technical, strategic, and economic viewpoints are partially conflicting.

The scientific debate about the new challenges concerning today's energy crisis is a focal point in many research areas. These research areas may contribute to overcoming the emerging difficulties in the oil industry through the strengthening of viable, sustainable, and socially acceptable new technologies. A recent comprehensive report, produced by the Technology and Policy Assessment function of the UK Energy Research Centre, UKERC (2009), examines about 500 international papers concerning the global oil depletion issue. It is an assessment of the evidence for a near-term peak in global oil production. Different theories and methodologies are examined with reference to the definition and estimation of 'reserves.' Two main approaches are highlighted. A 'realistic' vision considers the dynamics of extraction as a function of direct and indirect costs, energy return on energy investment (EROEI), strategic opportunities, and environmental constraints. An 'optimistic' approach assumes a future accessibility of oil resources, not relevant for today's economy, with the employment of new sophisticated technologies. For an introduction to the debate between realistic and optimistic approaches concerning crude oil perspectives see, for instance, Maugeri (2010) and Zecca et al. (2010). Within the optimistic approach, Greene et al. (2006) focus on the description of a transition to unconventional oil resources. They use a simulative risk model in order to combine alternative world energy scenarios from IIASA, USGS, and IEA studies. In their approach, the issue is not framed as a

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peaking time question for conventional oil, but in terms of a transition to unconventional oil resources.

The aim of the present paper is to combine the qualitative rationale expressed in Greene et al. (2006) with a different methodological perspective, based on diffusion of innovation theories (see, for instance, Guseo et al., 2007).

The main focus of this paper is devoted to oil reserves estimation through the characterisation of the *evolutionary production pattern* and statistical *Ultimate Recoverable Resource* (URR) determination. The URR for oil is the 'total amount of a finite resource which may be obtained at the end of extraction or production process as a result of all concurring forces.' For this reason, it must be jointly estimated from production evolution and not as a separate parameter as frequently observed in Hubbert's methodologies. This asymmetry, often assumed in a part of literature, may be questionable for a possible lack of motivation. See, among others, Mohr and Evans (2007, 2009) and Mohr (2010). Historical *production data* summarise the variable joint contributions of technological, economic, and social effects, including dynamic learning, on the production of a finite resource.

The statistical and forecasting literature on *Ultimate Recoverable Resource* (URR) estimation is quite limited, with some important exceptions. Two reviews in this area are those by Adelman and Jacoby (1979), and by Kaufmann (1988). Recent econometric extensions of the well-known logistic Hubbert model are provided by Kaufmann (1991), Cleveland and Kaufmann (1991), Pesaran and Samiei (1995), and Berg and Korte (2008). Oil aggregate demand is strongly correlated with the diffusion of the corresponding technologies in transport, heating appliances, electric power generation, etc. For these reasons, extraction data may be interpreted within a *diffusion of innovation* framework under commonly observed exogenous interventions that modify diffusion trajectories (see the generalised Bass model in Bass et al., 1994). Under a *finite life cycle* hypothesis, the unknown asymptotic *market potential* in a quantitative marketing context interprets the role of URR in the case of oil. Reserves are then indirectly obtained as a simple difference between estimated URR, through historical production data and actual cumulative production, avoiding overestimation effects due to 'financial reasons.' This approach, generalising the Hubbert one, was expressed in Guseo and Dalla Valle (2005) and in Guseo et al. (2007), where the Generalised Bass Model (GBM, see Bass et al., 1994) is the main tool in estimating locally perturbed extraction processes.

However, many systems exhibit complex dynamics that cannot be reduced to a single life cycle. We often observe multiple processes that may occur *simultaneously* or, more frequently, *sequentially*. The bi-logistic growth modelling by Meyer (1994) and the subsequent primer for the Loglet Lab Software by Meyer et al. (1999) may represent a first general approach in the analysis of simultaneous growth processes, based on the pioneering paper by Marchetti (1980) among others. We emphasise the simultaneous nature of the proposed bi-logistic or multi-logistic models, denoted by the subscript *ML*, for an implicit mathematical constraint that characterises the logistic framework components. As a matter of fact, each local distribution is a three parameter positive 'density' for $-\infty < t < +\infty$, with *positive* initial condition at $t=0$,

$$_{ML}z'(t) = \sum_{i=1}^{s} \frac{m_i r_i e^{-r_i(t-t_{pi})}}{(1+e^{-r_i(t-t_{pi})})^2}, \quad -\infty < t < +\infty, \tag{1}$$

where $_{ML}z'(t)$ denotes the mixed instantaneous production at time t, and for each cycle $i=1,2,\ldots,s$ we have a carrying capacity m_i, r_i is a 'steepness rate' or 'slope' and t_{pi} is the peak time of the unimodal symmetric local function. Notice that the local peak value, $P_i = m_i r_i/4$, is obtained for $t = t_{pi}$. Model (1) assumes that the s logistic processes are always active for each time t. This is surprising and contrary to intuition in the case of sequentially active (production) processes. This kind of modelling was firstly applied, in the energy context, by Al-Fattah and Startzman (2000). For a recent study concerning world oil production, see the iterated application to the analysis of production forecasts for the 47 most influential countries in terms of URR by Nashawi et al. (2010). A further application of the multi-logistic approach, denoted in the energy context as 'multi-Hubbert model' was presented in Imam et al. (2004) with reference to natural gas extraction and peaking times.

A similar approach in multi-processes modelling was recently proposed by Maggio and Cacciola (2009). The 'kernel' function, depicting local growth in production, is expressed through a special extension of the logistic (or Hubbert) traditional model, denoted by the subscript *L*, through trigonometric hyperbolic functions, namely,

$$_{L}z_i'(t) = \frac{m_i r_i e^{-r_i(t-t_{pi})}}{(1+e^{-r_i(t-t_{pi})})^2} = \frac{2P_i}{(1+\cosh(r_i(t-t_{pi})))} \tag{2}$$

by introducing in the mixed instantaneous production model at time t, $_{ML}\tilde{z}'(t)$, a shape parameter $0 < k_i < 1$ within each cycle, that symmetrically augments (for $k_i \ll 1$) the variability of local distribution of extractions over time,

$$_{ML}\tilde{z}'(t) = \sum_{i=1}^{s} \frac{2P_i}{(1+k_i \cosh(r_i(t-t_{pi})))}. \tag{3}$$

This interesting extension does not have a dual simple interpretable differential equation as in the pure logistic case. See, in particular, the corresponding formal representation discussed in Appendix A.

A first crucial aspect in modelling interpretable deviations from a standard *S*-shaped growth must describe local or significant interventions which do not rise from the internal dynamics of the cycle but depend upon external factors (political, technological, strategic, economic, etc.). A second crucial aspect is related to the previous surprising constraint induced by the logistic model with positive initial conditions. Logistic function is mathematically defined over the complete real line with a positive initial condition at time $t=0$, where $_{L}z_i'(0) = m_i r_i e^{-r_i t_{pi}} / (1+e^{-r_i t_{pi}})^2$, admitting a non-negative production contradictory preceding the observed process. A third crucial aspect is a possible confounding effect, induced by an over-parameterised multi-logistic modelling, that may erroneously exchange an exogenous intervention, for a new cycle for which no plausible interpretation is allowable.

For at least two decades in publicly reported data, non-conventional (heavy and sour) oils have usually been mixed with regular (light and sweet) crude oil, introducing uncertainties due to the aggregate behaviour of different resources. The emerging question is how to reconstruct component dynamics starting from an aggregate time series of global 'oil' production. Peaking time estimation and the rate at which production may be expected to decline following the peak are more difficult to determine.

In Section 2 we propose a two-wave model, namely a sequential multi-Bass model, for world oil production patterns and forecasting. Based on the diffusion of innovation theories, it gives a positive solution to the above-mentioned crucial problems occurring in a pure multi-logistic approach. In particular, the proposed two-wave model expresses correctly the sequential nature of the observed extraction processes and their partial overlapping. Moreover, the imputation of observed large deviations, due to external factors, is much more pertinent, and avoids