Worldwide Cheap and Heavy Oil Productions: A Long Term Energy Model

Renato Guseo

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 so that 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. 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 oil peak.
Keywords: sis topic (33, 55), oil depletion, diffusion process, NLS-ARMAX

1 Introduction

Oil is a non-renewable resource formed in the geological past, in 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 first one refers to light and sweet crude oils, while the second one brings together different resources: natural

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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 economy was very limited between 1900 and 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. 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 overcome 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 Center, 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).

The main focus of this paper is devoted to oil reserves estimation through the characterisation of the *evolutionary production pattern* and *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 the separate parameter usually observed in Hubbert's methodologies. Historical *production data* summarise the variable joint contributions of technological, economic and social effects, including dynamic learning, on a 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 (2006). 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). The unknown asymptotic *market potential* in a quantitative marketing context under a *finite life cycle* hypothesis interprets the role of URR in the case of oil. Reserves are then indirectly obtained as a simple difference between URR 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.

For two decades, non-conventional (heavy and sour) oils have been mixed with regular (light and sweet) crude oil so that 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 for world oil production pattern, and forecasting based on the diffusion of innovation theories. In Section 3 we compare the dynamics of mixed oil production with the corresponding refining capacity in order to understand possible ties and predictive symptoms.

2 A two-wave model for oil production and forecasting

The rate adoption curve of the Bass model, (BM), $z'(t) = (p+q_1z/m)(m-_1z)$, depicts a baseline evolution: a distribution that includes logistic function (Verhulst, 1838), and, therefore, Hubbert's model. The BM has been fully confirmed in quantitative marketing with reference to one life cycle products and was extended in Bass *et al.* (1994) with the introduction of a perturbation described by an integrable function $x(t)$ representing testable economic and strategic interventions.

The GBM is then characterised by a non-autonomous Riccati equation,

$$ {}_1z' = m\left(p+q\frac{{}_1z}{m}\right)\left(1-\frac{{}_1z}{m}\right)x(t) = \left(p+q\frac{{}_1z}{m}\right)(m-{}_1z)x(t), \tag{1} $$

and its closed form solution, under initial condition ${}_1z(0) = 0$, is

$$ {}_1z(t) = m\frac{1-e^{-(p+q)\int_0^t x(\tau)d\tau}}{1+\frac{q}{p}e^{-(p+q)\int_0^t x(\tau)d\tau}} = m\,{}_1F(t), \quad 0 \le t < +\infty. \tag{2} $$

Function ${}_1F(t)$ is a perturbed distribution. Notice that market potential m, URR in this case, will not affect peaking times and duration. It is a scale parameter. Function $x(t)$ modifies the geometry of adoptions over time and not the carrying capacity, m, or the diffusion parameters p and q. This aspect is not always preserved under inference, since asymmetric time evolution does not give rise to an "optimal design" with known biases if the half life span is not reached. We can model and test $x(t)$ in Equation (1) through some interventions, assuming a non-uniform distribution of their effects over time. Exponential types are usually effective, $x(t) = 1 + \sum_{i=1}^{3} c_i e^{b_i(t-a_i)} I_{t \geq a_i}$, in the case of memory effects due to external causes, e.g., permanent accumulating learning effects or, as an opposite situation, changes due to decaying effects.

The model in Equation (2) with three exponential interventions was examined in Guseo *et al.* (2007) with reference to world oil production covering a century, 1900–2002 (Campbell's and BP's mean daily production data per year). If we extend the previous application, including annual data until 2008 from BP, we observe a relevant departure in URR estimation, $4.17e6$ vs. $5.28e6$, and a stable behaviour of the first part of the model, during 1900–1980s, involving the estimation of well-known historical shocks (1951, 1973, and 1979).

The above-mentioned deviation in URR estimation may be imputed to a mixed production profile in the last two decades, suggesting a new approach based on a two-regime model, i.e., two subsequent waves that may be associated with two different oil "densities" that we simply denote by "cheap" and "heavy" oils. Unfortunately, these two products are not separated into different series. BP, for instance, considers a simple measure of aggregate oil production in barrels. We model previ-

Table 1 Results from GBM models with three shocks: OneWave2, 1900–2002, (Guseo *et al.* (2007); OneWave08, 1900–2008. TwoWave08 is a GBM with three shocks and a subsequent new heavy generation, BM, originating in 1986.

	mc	*pc*	*qc*	*c*1	*b*1	*a*1
TwoWave08	4.120330e+06	1.056836e-04	6.352327e-02	-3.004472e-01	6.344011e-02	8.056811e+01
OneWave08	5.280893e+06	8.249186e-05	6.334572e-02	-2.820173e-01	5.829027e-02	8.044347e+01
OneWave02	4.174551e+06	1.043901e-04	6.349702e-02	-3.218601e-01	5.674002e-02	8.050002e+01
	*c*2	*b*2	*a*2	*c*3	*b*3	*a*3
TwoWave08	7.229269e-02	7.174975e-02	5.105024e+01	-2.241371e-01	7.351826e-02	7.462345e+01
OneWave08	6.488241e-02	6.977838e-02	5.124170e+01	-2.281890e-01	6.479371e-02	7.458933e+01
OneWave02	7.177531e-02	7.187002e-02	5.107011e+01	-2.272032e-01	7.098011e-02	7.460001e+01
	mh	*ph*	*qh*	*ch*	*SSE*	R^2
TwoWave08	1.333679e+06	1.661451e-03	1.302502e-01	8.609658e+01	305920132	0.9999966
OneWave08					339274631	0.9999962
OneWave02					316947001	0.9999947

ous mixed compounds with an aggregate two-regime model, i.e.,

$$_2z(t) = m_c\,{}_1F(t) + m_h\,{}_2F(t-ch) I_{t \geq ch}, \tag{3}$$

where m_c is the URR of "cheap" oil (essentially crude oil and a part of NGL), ${}_1F(t)$ depicts the dynamics of the first wave as in Equation (2), with three exponential shocks, m_h is the URR of "heavy" oils and ${}_2F(t-ch)$ is a correspondingly shifted BM with parametric origin, ch. $I_{t \geq ch}$ is an indicator function. Under this new approach, we expect a stable identification of well-known historical shocks which precede the more recent regime's change due to the mixed accounting behaviour.

Nonlinear least squares (NLS) results are reported in Table 1. We notice that $m \simeq m_c + m_h = 5.46e6$, or 1991 Gbo (Giga barrels of oil), is the estimated total URR related to these two cycles. The three historical shocks are perfectly recognised as such and a new interpretation of the current dynamics is plausible. We

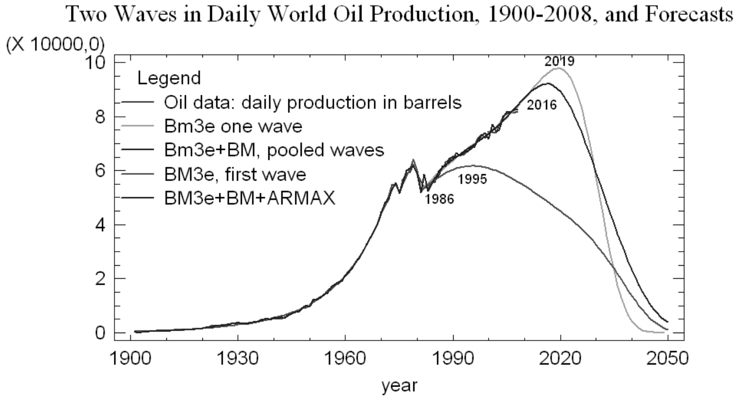

Fig. 1 Comparison between a two-wave world oil model and the corresponding one-wave GBM. Data sources: Campbell and BP's daily production in thousand barrels: 1900–2008.

observe that year 1986 is the estimated change point depicting the origin of "heavy" oils extraction. Year 1995 represents the cheap oil peak, while year 2016 denotes the new peaking point for aggregate production of "cheap" and "heavy" oils. Under a forced one-wave hypothesis, following Equation (2) with three shocks, the peak is located in year 2019, with the steepest behaviour of right tail. Figure 1 allows suitable comparisons among models, their components, and ARMAX sharpening of residuals. ARMAX sharpening is obtained under a hierarchical hypothesis on the relevance of different effects. Stochastic autocorrelated residuals $\varepsilon(t)$ have a limited impact, so that we solve a complex nonlinear least squares problem in presence of autocorrelated errors with a two-stage procedure relying on the non parametric robustness of NLS methodology determining the predicted values, ${}_2\hat{z}(t)$. If we consider the process $w(t) = {}_2z(t) + \varepsilon(t)$ where $\varepsilon(t)$ is an ARMA(p,q), then we can model $\Phi(B)(w(t) - a\,{}_2\hat{z}(t)) = \Theta(B)a(t)$, where $a(t)$ is a white noise, as a second stage estimate which allows a useful control on parameter a concerning the stability of first stage identification.

As a final remark, we underline the theoretical and empirical necessity for introducing a two-wave model in order to take into account different dynamics of heterogeneous oil resources even if we deal with mixed production data.

Under previous results that emphasise an imminent mixed oil peak (2016) driven by heavier resources, it may be crucial to understand the dynamic behaviour of refining processes as an essential tie among production, consumption, and environmental and strategic constraints.

3 Refining capacity: An emerging crunch?

High gasoline prices and related high diesel and heating oil prices are impacting economy and consumers. They are likely driven by concerns about the availability of spare crude oil production capacity. The study of dynamics in refinery capacity may suggest a different interpretation (see, for example, ICF, 2005).

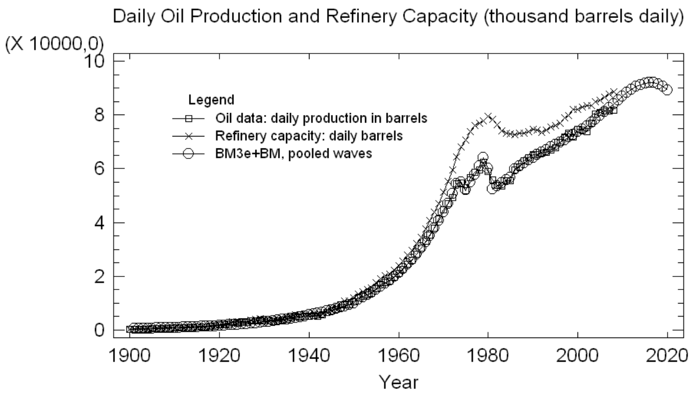

Fig. 2 Comparison between world oil refining capacity, world oil production, and two-wave modelling. Data sources: Campbell and BP's daily production and capacity in thousand barrels: 1900–2008.

Refinery "spare capacity" has eroded in the last two decades, in the sense that the ratio between daily refinery capacity and daily oil production capacity is quite similar to the one that occurred in the decades preceding the well-known shocks in the 1970's (see, in particular, Figure 2).

The increasing global demand for gasoline and diesel, and the regulatory policies that impose lower sulfur content are generating a trade-off between the demand for clean products and the availability of existing refining capacity from available heavier crude oil. This possible "capacity crunch" is not only a theoretical guess. We observe a global chilling in refining capacity growth (see Figure 2), but there is some different behaviour at the regional level. For instance, in the U.S.A. the number of the refineries fell to about 150 in the 2009 from more than 300 in 1982 (see *The New York Times*, 24 December 2009).

Environmental concerns and corresponding legislation are blocking new refineries and major expansions in the OECD countries. In Europe we only have diesel hydrocracker additions to existing plants. For a joint assessment of oil consumption and oil refining capacity in Europe and Eurasia, see Figure 3.

On the other hand, China alone is growing its refinery capacity at a very high rate, with plants more oriented to heavy and sour oils (see Figure 4). This strategy will

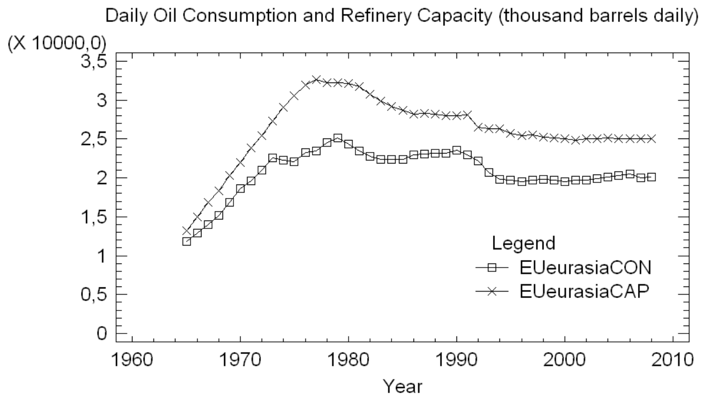

Fig. 3 Comparison between EU-Eurasia oil refining capacity and corresponding consumption. Data source: BP's daily consumption and capacity in thousand barrels: 1965–2008.

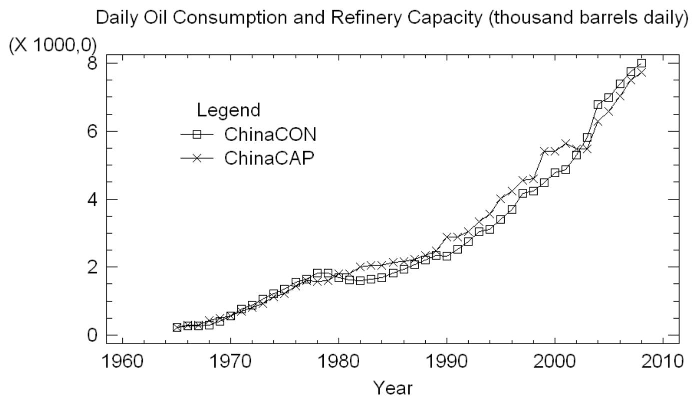

Fig. 4 Comparison between China's oil refining capacity and corresponding consumption. Data source: BP's daily consumption and capacity in thousand barrels: 1965–2008.

increase competition, putting upward pressure on refining margins. This aspect may partially explain the observed reduced ratio between refining capacity, which implies long term investments, and oil production, anticipating the risk of an imminent peak in oil production.

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