Energy Policy 37 (2009) 4761–4770

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

A variant of the Hubbert curve for world oil production forecasts

G. Maggio *, G. Cacciola

CNR–Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano", via Salita S. Lucia sopra Contesse 5, I-98126 Santa Lucia, Messina, Italy

ARTICLE INFO

Article history:
Received 20 March 2009
Accepted 9 June 2009
Available online 9 July 2009

Keywords:
Oil production
Hubbert theory
Oil peak forecasts

ABSTRACT

In recent years, the economic and political aspects of energy problems have prompted many researchers and analysts to focus their attention on the Hubbert Peak Theory with the aim of forecasting future trends in world oil production.

In this paper, a model that attempts to contribute in this regard is presented; it is based on a variant of the well-known Hubbert curve. In addition, the sum of multiple-Hubbert curves (two cycles) is used to provide a better fit for the historical data on oil production (crude and natural gas liquid (NGL)).

Taking into consideration three possible scenarios for oil reserves, this approach allowed us to forecast when peak oil production, referring to crude oil and NGL, should occur.

In particular, by assuming a range of 2250–3000 gigabarrels (Gb) for ultimately recoverable conventional oil, our predictions foresee a peak between 2009 and 2021 at 29.3–32.1 Gb/year.

1. Introduction

Oil (or petroleum) is the most used energy source worldwide, accounting for 36.4% of primary energy consumption (EIA, 2006) and 94.5% of global energy used for transportation (OECD/IEA, 2008a).

Therefore, the importance of this resource is unquestionable, but several negative aspects are either directly or indirectly related to its use; in particular, consequent damage to environmental equilibrium and energy dependence on politically unstable regions (Middle East, South America), both of which will probably increase in the future, are prominent concerns.

Italy is not immune from these problems, because it is one of the lowest energy producing countries in the world and depends heavily on energy imported from outside the country; in fact, it is eighth in the world for net oil imports – 1533 thousand barrels per day (kbpd) in 2007 – and 14th for oil consumption (1702 kbpd in 2007); moreover, it ranks fifth among non-producing oil consumers, i.e., countries whose oil production is 10% or less of their needs (EIA, 2009a).

Another significant, disquieting fact is that Italy has one of the highest vehicle to population ratios in the world, ranking sixth with 666 road motor vehicles per 1000 inhabitants in 2006 (OECD, 2008).

In a wider context, the availability of oil is a very relevant problem at present, because oil, like other fossil fuels, has a limited lifespan.

In this paper, a model to estimate the year in which world oil production will reach its maximum (peak) is proposed, a peak that several other studies agree is forthcoming.

Numerous contributions to scientific literature or on the web on this subject confirm that this type of evaluation is not a mere mental exercise. In fact, oil production will begin a fatal decline just after the peak is reached, causing serious but, as yet, unforeseeable consequences in terms of our global economy and political stability.

2. World oil production data

The following three sources have been referenced for historical data on world oil production:

- BP Statistical Review of World Energy, June 2008 (BP, 2008). Data published by Beyond Petroleum (ex British Petroleum), a multinational petroleum company with headquarters in London.
- ENI World Oil and Gas Review 2008 (ENI, 2008). Data provided by the Ente Nazionale Idrocarburi (National Hydrocarbons Agency), an Italian multinational oil and gas company.
- EIA International Petroleum Monthly, January 2009 (EIA, 2009b). Data from the Energy Information Administration, a section of the US Department of Energy (DOE).

These data are reported on in Fig. 1, in which there are noticeable differences in the values of oil production and the time periods covered. In the same figure, two additional curves are shown, both derived from data on the EIA website (EIA, 2007, 2009b): one refers to the world's production of crude oil (including lease condensate), the other to the sum of crude oil and natural gas liquid (NGL) production.

Specifically, the term "oil production" does not refer to only crude oil but also includes other oil categories from unconventional

* Corresponding author. Tel.: +39 090 624243; fax: +39 090 624247.
E-mail address: gaetano.maggio@itae.cnr.it (G. Maggio).

0301-4215/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2009.06.053

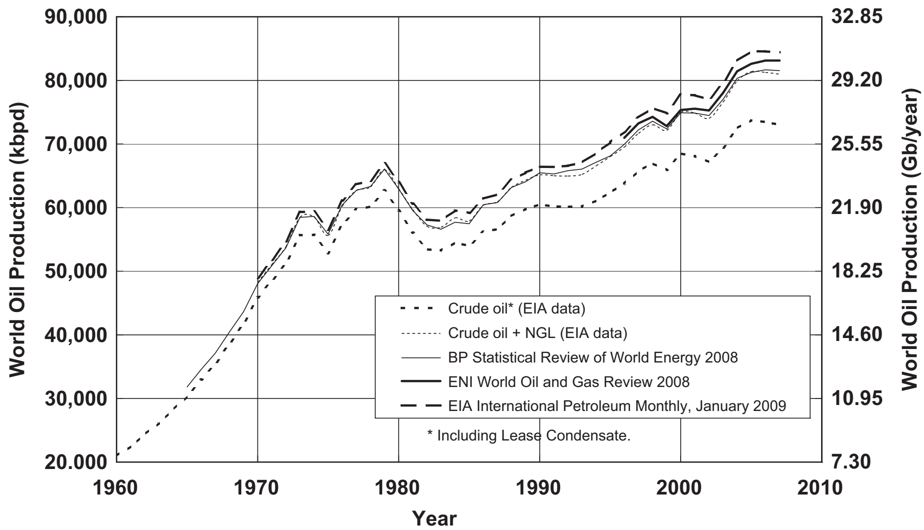

Fig. 1. World oil production historical data from different sources.

sources, mainly oil sands, oil shales, and extra-heavy oil; sometimes the conversion of coal, natural gas, and biomass into liquid hydrocarbons via processes (such as the Fischer-Tropsch synthesis) carried out in coal-to-liquids (CTL), gas-to-liquids (GTL), and biomass-to-liquids (BTL) plants is also included.

Currently, all of these unconventional sources represent oil obtained by costly, difficult methods of extraction/production, so they do not contribute significantly to the world's oil demand; nevertheless, they are expected to gain more relevance in the coming years.

Natural gas liquids and "processing gain" are two additional categories in oil production at present. The former are hydrocarbons obtained from liquid fractions of natural gas; the latter is the volumetric increase achieved in refining (cracking and distillation) processes, when crude oil is transformed into (globally) less dense products. NGL consists of natural gas plant liquids (NGPL) and lease condensate, a mixture comprised of mainly pentanes and heavier hydrocarbons recovered as a liquid in lease separation facilities. Generally, the condensate is blended with crude oil stream for refining; therefore, most producers include it in the reported volume of crude oil production.

Other oil categories that should be considered reserves/resources rather than production are offshore/arctic oil and what is called enhanced oil recovery (EOR). Offshore oil extracted from deepwater or ultra-deepwater and that recovered in Arctic areas can be categorized as conventional oil, but they can only be obtained by unconventional means (i.e., new technologies that are not yet fully developed). EOR is also based on technologies that are not yet fully developed, and it is one of the most important categories in the "reserve growth" of existing fields, which depends, particularly, on high-level investment and/or improvements in exploration and extraction techniques (e.g. advanced drilling systems). Several EOR methods are under development (both for conventional and unconventional oil), and the most promising ones seem to be those involving miscible displacement, e.g. the injection of CO_2 to obtain hyper-production of oil.

In light of these issues, differences observed in the historical data on oil production (~1.2 Gb/year at most) can be attributed, essentially, to discrepancies in the categories of oil each of the cited sources considers (e.g. EIA is the only source that explicitly includes processing gains in the definition of oil production); in particular, unconventional oil is taken into consideration in different proportions. Data reported by Beyond Petroleum (abbreviated to BP hereafter) refer almost exclusively to crude oil and NGL, while the other two sources (ENI, EIA) include unconventional oil, but the exact definition of this category is difficult to understand.

There is general agreement on the amount of oil produced to date (cumulative production), which is reported to be approximately 1100 Gb (1128 Gb in OECD/IEA (2008a); 1180 Gb in Hutter (2009)). However, data on oil reserves (i.e., the amount of oil that is expected to be recovered in the future from known fields under current, expected economic conditions, using existing technology) and on oil resources (i.e., the amount of oil of foreseeable economic interest that can be recovered, potentially, from undiscovered fields or unexplored extensions of known fields) are more controversial. In fact, as the French oil consultant Petit has proven (2003), there are considerable differences in oil reserve data from various sources "due to the lack of a common definitional framework and political distortions". Analogously, Laherrère (1990) and Campbell (1997) have asserted repeatedly that "the reporting of reserves is a political act".

Thus, estimates of reserves and resources globally range from 1000 to 2000 Gb or more (2843 Gb in Hutter (2009)), of which resources are estimated anywhere from a few hundred to over 1000 Gb (805 Gb in OECD/IEA (2008a), for conventional oil and NGL). In OECD/IEA (2008a), the ultimately recoverable conventional oil (as the sum of production, resources, reserves, and reserve growth) is estimated at approximately 3500 Gb; the total long-term potentially recoverable oil, including unconventional resources (oil sands, extra-heavy oil, and oil shales), is estimated at around 6500 Gb; a significant increase to 9000 Gb is reported when coal-to-liquids and gas-to-liquids are added.

Data on oil reserves and resources, together with cumulative production, are useful in making forecasts for future oil production (see estimated ultimate recovery (EUR) concept below).

3. Hubbert peak theory

This paper uses historical data on world oil production and aims to determine both the year of peak world oil production and the future trends in production itself.

This subject has already been investigated by many experts in the field. In particular, geophysicist Marion King Hubbert (1903–1989) first proposed a general approach now known as the "Hubbert Peak Theory", which was based on historical data on Pennsylvania's anthracite coal production. In a groundbreaking paper (Hubbert, 1956), he applied this theory to crude oil production in the US Lower 48 states (Alaska and Hawaii were excluded as they had not yet joined the Union) and correctly predicted its peak in the early 1970s.

The Hubbert curve is usually described by the following equation:

$$P = \frac{2P_M}{1 + \cosh[b(t - t_M)]} \tag{1}$$

in which P is oil production at time t, P_M peak production, b a parameter which accounts for the slope of the curve, and t_M the year corresponding to the peak.

Thus, P_M is the maximum of the curve, and the area under the curve is equal to $U = 4P_M/b$, where U represents the "estimated ultimate recovery", i.e., the amount of oil globally recoverable (or better, cumulative oil production until reserves are depleted).

Therefore, only two of the three parameters (P_M, b, and t_M) in Eq. (1) are independent: in fact, the slope can be calculated as $b = 4P_M/U$, once the value of Ultimate is fixed.

In recent years, many authors (particularly, Laherrère (1997, 2000, 2002a); Campbell (1996, 2002)) were stimulated by the economic and political implications of energy problems and turned their attention to the Hubbert's theory in an attempt to apply the analysis to other countries and forecast the evolution of future world oil production. However, some researchers – the optimists (e.g. Adelman, Odell, and Nehring) – are in complete disagreement with the Hubbert's theory and assert that the problem of oil depletion has been over-emphasized; some scientists have denied the problem even exists (e.g. Petit (2003) and economist Lynch (2003)). On the other hand, the pessimists (e.g. Bentley, Deffeyes, Duncan, Campbell, and Laherrère in his first studies) suggest that world oil production has already peaked.

Some of these analysts have proven that the Hubbert's model has disadvantages and limitations, in particular, the following:

- It assumes oil production is only time-dependent and does not take into account the effect of possible technological and/or economic factors.
- It provides a forecast with only one peak in oil production, which seems valid when applied but only in a small number of cases, i.e., oil production in the US Lower 48 states (already proven) or countries with a large number of oil fields and basins, such as the Former Soviet Union.

In the literature, there are some models that attempt to overcome these limitations (Duncan and Youngquist, 1998; Holland, 2006; Laherrère, 1997, 2000, 2002a; Rehrl and Friedrich, 2006). In particular, Laherrère (1997, 2000) proposed a model characterized by several cycles and oil production peaks, adopting an approach he called the "multiple-Hubbert modelling."

His concept is supported by convincing evidence from historical data on oil production in several countries (Laherrère (1997, 2000), illustrates that oil production in France, the Netherlands, and the United Kingdom cannot be reproduced with a single Hubbert cycle). Therefore, Laherrère puts forward the argument that the "multiple-Hubbert" approach should be applied to determine future trends in world oil production, which has already peaked in the late 1970s and is ready to peak again in the first decades of the 21st century.

In accordance with these studies, Laherrère's approach (1997, 2000) is applied in this paper.

Criticism of the Hubbert model in terms of the irrelevance of economic, political, and technological factors is valid; the model, although simple, nevertheless, still represents a reasonable approach, for the effect of such factors –unless they are substantial, which at present is unforeseeable –will not be, in our opinion, relevant enough to radically distort the oil production curve.

3.1. A variant of the Hubbert curve

A variant of the Hubbert curve, taken from Laherrère (2000), is considered here

$$P = \frac{2P_M}{1 + k\cosh[b(t - t_M)]} \tag{2}$$

with $k \leq 1$.

The maximum and the area under the curve of this variant are, respectively

$$P_{max} = \frac{2P_M}{1 + k} \tag{3}$$

$$U = \frac{4P_M}{b} \frac{\ln(1 + \sqrt{1 - k^2}) - \ln(k)}{\sqrt{1 - k^2}} \tag{4}$$

Eqs. (3) and (4) are new and are reported on for the first time in this paper (see Appendices A and B for details). It should be noted that both these formulas provide –as expected –maximum and area values, corresponding to the "classic" Hubbert curve, when k tends to 1. Therefore, this approach also includes the classic Hubbert model that is most often adopted in the literature.

As stated above, Eq. (2) was reported in Laherrère (2000), but it was not applied there. The reason this relationship was mentioned is related to the fact that Laherrére, commenting on the famous plot published by Hubbert (1956), observed "it is interesting to note that the Hubbert graph has a fatter top than computed with the above formula (author refers here to the classical Hubbert curve)", and later in the text, he stated "to obtain the same fat top it is necessary to add another parameter k".

It should be noted that Hubbert never presented a mathematical model, but did his computations graphically. Therefore, it is evident that Laherrére introduced Eq. (2) only to justify the different "shape" of the peak resulting from applying Eq. (1) as compared to that of the curve presented by Hubbert (1956); he did not use the formula in his calculations. Furthermore, in the literature, despite the numerous variants of the Hubbert curve that have been proposed and compared (e.g. Brandt (2007); Witten (2006)), to our knowledge there are no other studies based on the variant applied here.

It is a verifiable fact that Eq. (2) provides a more accurate fit, especially for high values of area (i.e., the Ultimate), which could result in a significant shift in both the peak value and corresponding peak year as well as in a change in the curve's shape.

3.2. The multiple-Hubbert approach

By using the "multiple-Hubbert" approach, Eq. (2) may be generalized further as

$$P = \sum_{i=1}^{N} \frac{2P_{M_i}}{1 + k_i \cosh[b_i(t - t_{M_i})]} \tag{5}$$

N being the number of cycles; analogously, Eqs. (3) and (4) may be written for each cycle by substituting the parameters P_M, k, U and b with specifics that correspond to each cycle.

Obviously, such an approach is more complex than that based on a single cycle, because the number of fitting parameters becomes $3N$ using Eq. (5). Thus, the key question emerges: how many cycles have to be considered?

Laherrère (1997) states that oil production in every country can be described with 3–4 cycles at most, "just as a sound can be modelled with few harmonics". He chose three cycles to model world oil production (see Laherrère, 2000): the first cycle for the oil peak in the late 1970s with an Ultimate $U_1 = 150$ Gb; the second for the second peak (yet to come) in conventional oil with an Ultimate $U_2 = 1850$ Gb (a global Ultimate of 2000 Gb for crude oil and NGL—1800 Gb for crude and 200 Gb for NGL), and the third cycle for unconventional oil with an Ultimate $U_3 = 750$ Gb.

Our intention, however, is to not focus on the cycle for unconventional oil production, because available estimates of this figure differ considerably and are questionable; furthermore, data on the present production of unconventional oil show its percentage in terms of total world oil production is insignificant (according to the latest EIA data reported by Foucher (2008), referring to May 2008, unconventional oil amounts to 3.42 million barrels per day (mbpd), while all liquid production is 86.05 mbpd; therefore, the production of unconventional oil accounts for only approximately 4% of the world's total oil production. An analogous percentage can be derived from data reported in OECD/IEA (2008a)); for these reasons, a valid curve for this cycle is difficult to obtain. Therefore, we performed a fitting of oil production data on crude oil and NGL only.

Considering oil production as the sum of two cycles, Eq. (5) becomes

$$P = \frac{2P_{M_1}}{1 + k_1 \cosh[b_1(t - t_{M_1})]} + \frac{2P_{M_2}}{1 + k_2 \cosh[b_2(t - t_{M_2})]} \tag{6}$$

which involves six fitting parameters (P_{M_1}, k_1, t_{M_1}, P_{M_2}, k_2, and t_{M_2}).

However, based on preliminary evaluations that showed that the value of k_1 always converged to 1 even if it was left free to vary, fitting parameters were reduced to five.

The final algorithm can be summarized as follows:

- Oil production:

$$P = \frac{2P_{M_1}}{1 + \cosh[b_1(t - t_{M_1})]} + \frac{2P_{M_2}}{1 + k_2 \cosh[b_2(t - t_{M_2})]} \tag{7}$$

- Peak productions:

$$P_{\max_1} = P_{M_1}, \tag{8a}$$

$$P_{\max_2} = \frac{2P_{M_2}}{1 + k_2} \tag{8b}$$

- Slopes:

$$b_1 = \frac{4P_{M_1}}{U_1}, \tag{9a}$$

$$b_2 = \frac{4P_{M_2}}{U_2} \frac{\ln(1 + \sqrt{1 - k_2^2}) - \ln(k_2)}{\sqrt{1 - k_2^2}} \tag{9b}$$

- Global Ultimate:

$$U_{tot} = U_1 + U_2 \tag{10}$$

3.3. Choice of the oil production reference curve and the Ultimate range

To do a fitting with two Hubbert cycles, we need a world oil production curve referring to crude oil and NGL. The reference curve used for this purpose is from the historical data on oil production by Beyond Petroleum (BP, 2008). We preferred this curve, instead of that which can be obtained from the sum of crude oil and NGL from EIA data (see the thin-dashed curve in Fig. 1), because corresponding NGPL data were available from only 1970 onwards (EIA, 2009c).

BP oil production data cover the period from 1965 to 2006; we then added data from 1950 to 1964 published by Brown (2008) – founder and president of the Earth Policy Institute (EPI) – and compiled by Worldwatch Institute from the US Department of Defence and the US Department of Energy. The data reported by Brown (2008) include, as a whole, the period 1950–2007, and oil production from unconventional sources and processing gain; however, in the period 1950–1964, production was from virtually crude oil alone.

The curve obtained (58 values) was used as a reference for all fittings presented in this paper with two Hubbert cycles.

In terms of the Ultimate (or EUR), in the literature there are several estimates. In particular, World Energy Outlook 1998 (OECD/IEA, 1998) reported a range of 2100–2800 Gb (from Masters et al. (1994)), with an average value of 2300 Gb for crude oil only; in the same book, a value of 1800 Gb (from Campbell (1997)), regarded pessimistic by many, is mentioned. In World Energy Outlook 2001 (OECD/IEA, 2001), however, a value of 3345 Gb (from USGS (2000)) for crude oil and NGL (3021 and 324 Gb, respectively) is reported; this value, regarded too high by several authors, includes 730 Gb of reserve growth. Recently, in World Energy Outlook 2008 (OECD/IEA, 2008a), a value of 3577 Gb was given as ultimately recoverable conventional oil and NGL (1128 Gb from cumulative production, 1241 Gb from remaining reserves, 805 Gb from undiscovered resources, and 402 Gb from reserve growth).

Nevertheless, most estimates fall in the range of 2000–3000 Gb (see Andrews and Udall (2003) and Petit (2003) for a comparison), but it is not easy to understand whether or not these include unconventional oil or to what extent.

In particular, in recent papers of Laherrère (2002b, 2005, 2006), an Ultimate of 2250 Gb is reported for crude oil and NGL (2000 and 250 Gb, respectively). This figure was used as our reference lower limit value.

The upper limit, which also referred to crude oil and NGL, was fixed at 3000 Gb and based on the most recent update of 21 independent estimates (Hutter, 2009), yielding an average global Ultimate – which sometimes included oil from unconventional sources – of 4023 Gb (of which 2843 are remaining reserves and resources).

Therefore, in this study, three possible scenarios were considered for the value of Ultimate (referring to crude oil and NGL): $U_{\text{tot}} = 2250$ Gb, $U_{\text{tot}} = 2600$ Gb (intermediate scenario, an approximate average of the two limiting cases), and $U_{\text{tot}} = 3000$ Gb.

Ultimate U_1 of the first Hubbert cycle refers to the peak of oil production in 1979 and was fixed at 150 Gb in accordance with Laherrère (2000). Therefore, Ultimate U_2 of the second Hubbert cycle is determined as the difference between U_{tot} and U_1 (see Table 1).

In our opinion, based on the present state-of-the-art, a scenario with an Ultimate greater than 3000 Gb for crude oil and NGL is improbable; however, this paper includes additional evaluations (see next paragraph) to provide an idea of what one could expect if the value of Ultimate were higher.

4. Results and comments

Results are shown in Figs. 2–6. Fig. 2 refers to the most pessimistic scenario among those considered ($U_{\text{tot}} = 2250$ Gb),

Table 1
Fitting results for a global Ultimate (crude+NGL) between 2250 and 3500 Gb.

Ultimates			Calculated values									
U_1 (Gb)	U_2 (Gb)	U_{tot} (Gb)	Slopes		k_2	$P_{M_1}=P_{max_1}$ (Gb/year)	t_{M_1}	P_{M_2} (Gb/year)	Peak value (Gb/year)	Peak year	MAE (Gb/year)	MSE (Gb/year)
			b_1	b_2					P_{max_2}	t_{M_2}		
150	2100	2250	0.238	0.058	0.783	8.9	1975	26.1	29.2[a]	2009	0.384	0.543
150	2450	2600	0.234	0.060	0.385	8.8	1975	21.3	30.7	2015	0.358	0.518
150	2850	3000	0.232	0.063	0.205	8.7	1975	19.3	32.1	2021	0.357	0.517
150	3350	3500	0.231	0.064	0.115	8.7	1975	18.6	33.4	2029	0.358	0.518

MAE = mean absolute error.
MSE = mean-square error.

[a] The corresponding peak production is 29.3 Gb/year due to the residual effect of the first Hubbert cycle.

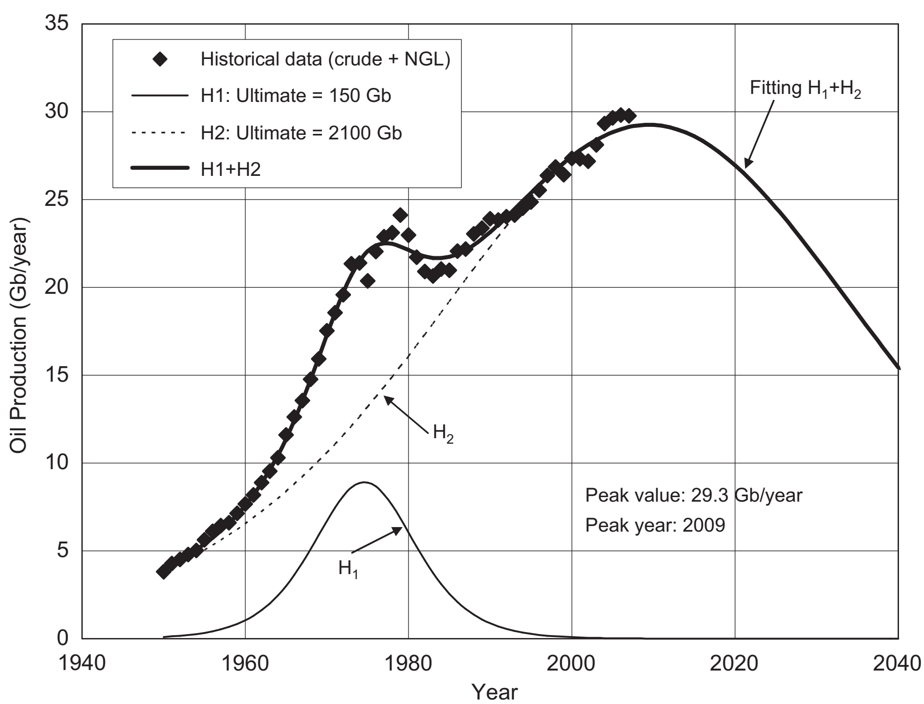

Fig. 2. World oil production (crude+NGL) calculated for a global Ultimate of 2250 Gb.

one in which the peak of the world's oil production of crude oil and NGL is 29.3 Gb/year and occurs in 2009. Such a forecast –even if it is not in line with public opinion and is impossible to validate as 2009 has only just begun –can be confirmed, in part, by the drop in production from 2006 to 2007 and by recent data from EIA (summarized by Koppelaar, 2009) reporting that the all-time high production of crude oil (including lease condensate) stands at 74.83 mbpd, which was reached in July 2008; the latest figure available shows a decrease of about 3.0 mbpd (71.91 mbpd in February, 2009). In our opinion though, it is too early to say whether or not this peak is real (as stated by Cohen (2009)) or if it will be followed by a new, more or less pronounced, rise. The observed decrease in production is not "proof" of the peak theory, because it is also related to the global economic downturn (decreased oil demand) and the OPEC members' decision to slash their oil output, effective January 2009, in an attempt to slow the decline in oil prices (OPEC, 2008).

In Fig. 2, one can observe that values calculated from the fitting differ from those in historical data on the last four years of oil production. However, the maximum difference is negligible (~0.82 Gb/year in 2006) and can be justified –if the value of Ultimate (2250 Gb for crude oil and NGL) is assumed reliable –by considering the fact that historical data on production from 2004 to 2007 could represent an anomalous rise, which might be followed by production values in line with the forecast curve again.

Results shown in Fig. 3 refer to the intermediate scenario with a global Ultimate of 2600 Gb, and are not more encouraging than those in Fig. 2. In fact, from this plot, one can deduce that the peak of oil production (crude oil and NGL) will be 30.7 Gb/year and delayed six years (2015), compared to the lower limit scenario. Results of the most optimistic scenario (3000 Gb of Ultimate) are presented in Fig. 4, which forecasts that oil production will peak in 2021 at 32.1 Gb/year.

In the two latter cases, there is more agreement (vs. the first scenario in Fig. 2) between historical and, in particular, the most recent data on oil production, and this study's estimates.

To summarize, our analysis has led to the conclusion that within 12 years at most, the greater part of world oil production, defined by crude oil and NGL, will reach its peak then start declining.

It should be noted that in all the cases examined, peak production of and the peak year for crude oil and NGL coincide almost precisely with those in the second Hubbert cycle (curve H_2 in Figs. 2–4), for the first Hubbert cycle (curve H_1 in Figs. 2–4) has already exhausted its effect.

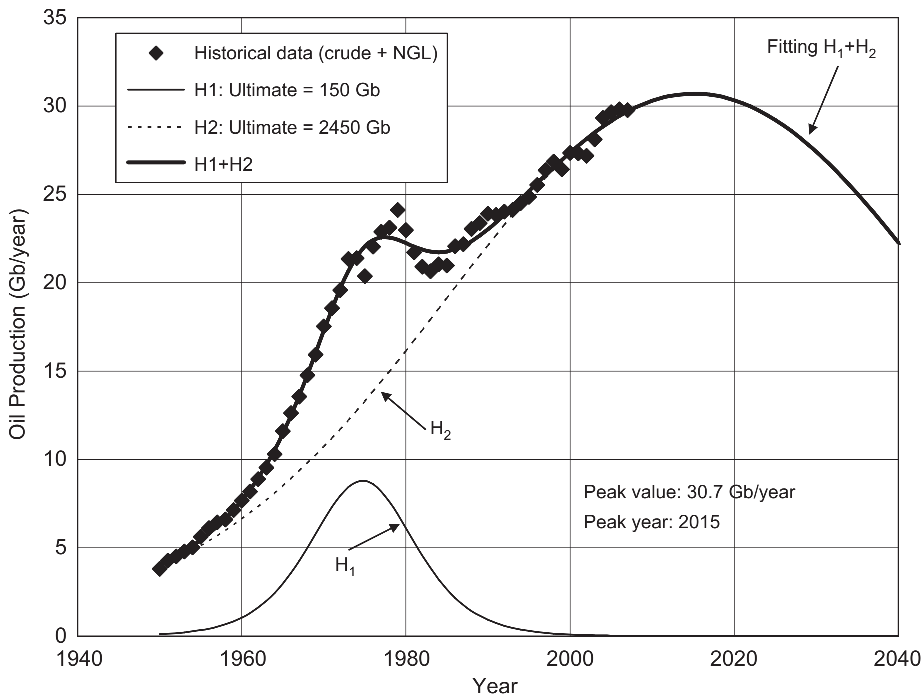

Fig. 3. World oil production (crude+NGL) calculated for a global Ultimate of 2600 Gb.

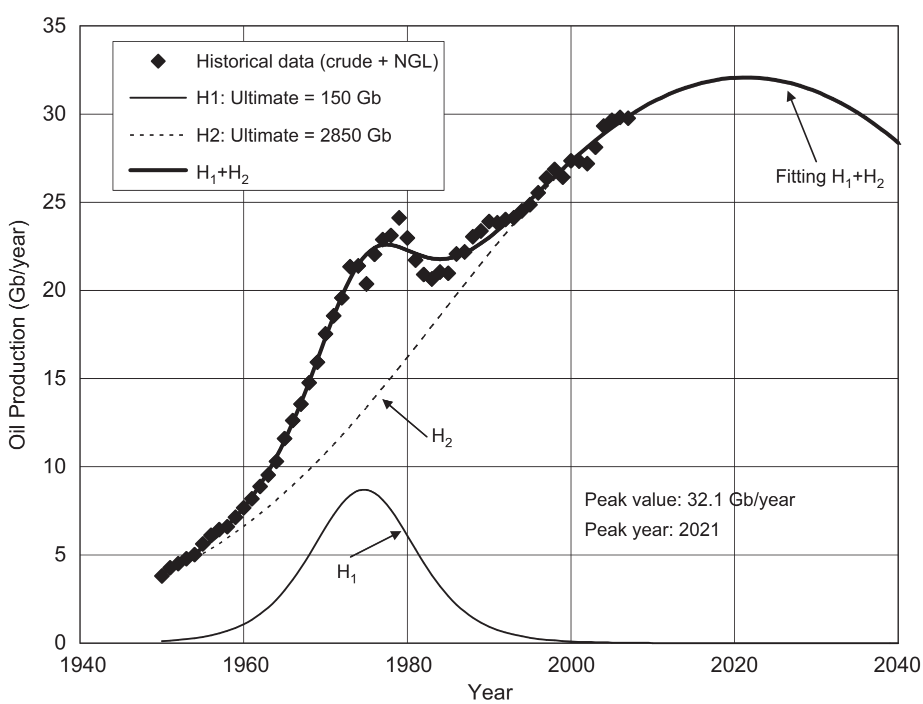

Fig. 4. World oil production (crude+NGL) calculated for a global Ultimate of 3000 Gb.

Comparisons of the results of the three scenarios are in Table 1 and Fig. 5. In particular, Table 1 reports all values of the fitting parameters calculated for the three cases; one additional scenario with a global Ultimate (crude oil and NGL) of 3500 Gb is also shown. In addition to what has already been mentioned, the results in Table 1 illustrate the following: the value of parameter k_2 decreases when the Ultimate increases, dropping from roughly 0.78 to about 0.12 (a value very different from the 1.0 in the classic Hubbert curve traditionally used in the literature); the mean absolute error (MAE) between historical values and estimated values is always lower than 0.40 Gb/year, and the mean-square error (MSE) is lower than 0.55 Gb/year.

Furthermore, the peak corresponding to the least probable case, that with a global Ultimate of 3500 Gb, is 33.4 Gb/year and occurs in 2029.

In Fig. 5, one can observe how the peak value, peak year, and shape of the production curve change when the value of Ultimate ranges between 2250 and 3000 Gb. Fig. 6, instead, provides a

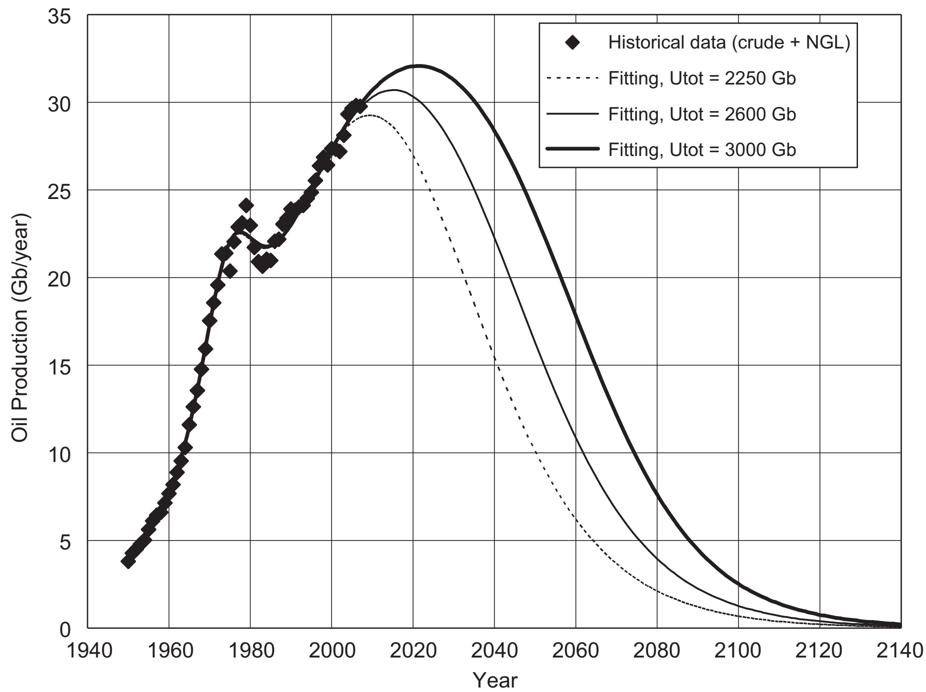

Fig. 5. Comparisons of world oil production (crude+NGL) calculated for a global Ultimate between 2250 and 3000 Gb.

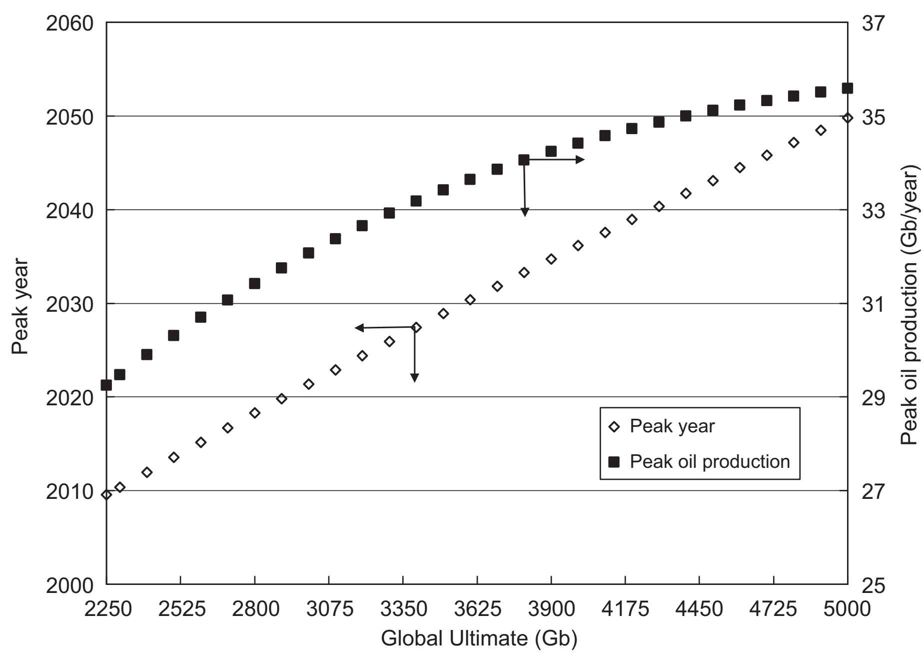

Fig. 6. World oil production (crude+NGL) peak value and peak year calculated as a function of the global Ultimate.

useful chart for determining peak values (production and year) once the global Ultimate for crude oil and NGL is known. In this figure, the values of Ultimate were not limited to those in the three main scenarios (analysis was extended to a value of 5000 Gb).

Fig. 5 also shows that in all three scenarios, curves tend toward null production asymptotically in 2140. Of course, this should not lead to the conclusion that the "lean" years are in the distant future, for the effects of reduced oil production would be felt well before 2140 and may, to some extent, have already started, or will most certainly do so when the world nears its oil production peak. In fact, there is general agreement among researchers and analysts that the real problem is not the end of oil but the end of plentiful, cheap oil.

Finally, it should be noted that the forecasts, in this paper, are in agreement with results in the literature. For instance, support for both peak production and the peak years may be found in Andrews and Udall (2003), Foucher (2008), Hirsch (2007) and Petit (2003). In fact, from these references, the most recent estimates in the majority of cases forecast a peak between 2010 and 2030. Therefore, our predictions are sufficiently close to those of other scientists, even if their estimates sometimes include oil from unconventional sources, which our analysis does not consider. For crude oil and NGL only, the calculated average of

17 forecasts by different organizations/agencies, and analysts, and reported on by Foucher (2008), puts the peak year and peak production in 2009 and at 30.9 Gb/year, respectively.

How many years, then, might the peak be delayed as a result of unconventional sources of oil?

In terms of formulating an answer, some general considerations follow: if the peak of crude oil and NGL production occurs in the next few years, the amount of oil produced from unconventional sources would not be relevant enough to change the future scenario significantly; however, if the peak of crude oil and NGL occurs later, in the meantime the production of unconventional oil could increase enough (from OECD/IEA (2008b), it can be estimated that global oil production from processing gains, shale oil, oil sands, and arctic/ultra-deepwater will be approximately 12% in 2030 and 20% in 2050) to affect the peak itself (a third peak associated with unconventional oil could also occur, but would probably be less pronounced). Nevertheless, according to a comparison of estimates (Foucher, 2008), we should not expect a significant shift in the peak year. In such a case, oil prices should even increase; therefore, the era of abundant and cheap oil would also end.

It can be argued that unconventional oil, rather than significantly affecting the oil peak, will most likely affect the "depletion year" (i.e., the year oil supplies will be completely exhausted), which depends, indirectly, on production. In fact, if production drops below a critical level and cannot satisfy present consumption (or future demand, which will probably be higher), necessity will force considerable reliance on reserves (or increase investment in oil/hydrocarbons that are difficult to extract); otherwise, a serious alternative and/or substitute for oil (e.g. widespread use of renewable energy sources) should be employed.

5. Impacts of the peaking of world oil production

World energy demand/consumption has increased 25% in the last decade (EIA, 2006) and is expected to rise another 44% from 2006 to 2030 (EIA, 2009d). Fossil fuels currently account for 86% of the world's primary energy consumption (36% oil, 27% coal, and 23% natural gas), renewable sources (solar, wind, geothermal, biomass, and hydroelectricity) account for about 8%, and nuclear power about 6% (EIA, 2006).

There are substantial and unsustainable differences in primary energy consumption among industrialized, developing, and less-developed countries: the US alone, with less than 5% of the world's population, consumes about 25% of the world's energy (Markham, 2008).

The thirst for fossil fuels (oil, natural gas, and coal) will probably not decrease in the future, and this could exacerbate the environmental problems. In addition, gas and coal, like oil, are exhaustible resources. Renewable sources are constrained by their inherent variable, intermittent nature. Like most oil alternatives, nuclear power is used almost exclusively for electricity generation, which represents less than one-third of the world's final energy consumption.

A possible effect of peak oil (and the consequent rise in oil prices) is that economic concerns could override environmental issues that have emerged as a major preoccupation in industrialized countries (under the Kyoto protocol, signed in Japan in 1997, industrialized nations agreed to collectively reduce greenhouse gas emissions 5.2% below their 1990 level, by the year 2012). The present recession has demonstrated that economic concerns might be a convincing reason for a tangible reduction in the consumption of fossil-fuel-based energy systems in general and, specifically, petroleum-based transportation fuels: US gasoline consumption fell by 0.5% in the first two months of 2008 compared to a drop of 0.4% in the whole year 2007 (Langfitt, 2008). Measures to mitigate the impact of peak oil could be undertaken, i.e., waste recycling, biomass conversion, adoption of incentives to support the combined use of sustainable energy sources (subsidies, tax relief, regulatory mandates, efficiency guidelines, etc.; the European Commission has proposed a binding target of increasing the share of renewable energies in the EU from the current level of less than 7% to 20% by 2020 (CEC, 2007)). R&D for the transition to hydrogen-based energy systems and the implementation of technologies for efficient use, production, and distribution of energy should also be supported.

Peak oil could be a great challenge for mankind in terms of reconciling the world's energy demand with environmental protection, while maintaining or improving current standards of living in both developed and developing countries. However, according to the Hirsch et al. report (2005), timely actions are needed to avoid economic, social, and political shocks: "viable mitigation options exist on both the supply and demand sides, but to have substantial impact, they must be initiated more than a decade in advance of peaking".

6. Conclusion

This paper proposes a model to determine the peak and the behaviour of world crude oil and NGL production, i.e., abundant and (currently) less expensive oil. Even though there are several evaluations of this subject in the literature, another contribution to the topic may be of interest, especially as this study is based on a variant of the Hubbert curve traditionally used for this purpose.

The model proposed here adopts a "multiple-Hubbert" approach that involves the use of a number of cycles (in our case, two) to forecast future trends in oil production from historical data.

Based on reliable data on the production of crude oil and NGL, results yielded a production peak ranging between 29.3 and 32.1 Gb/year, occurring between 2009 and 2021. As confirmed by other studies, it also seems probable that the peak is forthcoming and, in our opinion, the rise in oil prices recorded in the first months of 2008 (US light sweet crude peaked at $147.27 in July 2008) could be related, in part, to the proximity of this event, to the emerging economies of several countries (e.g. oil consumption in China almost doubled –from 4179 to 7855 kbpd – between 1997 and 2007; India's increased one and a half times –from 1828 to 2748 kbpd – in the same period (data from BP (2008))), to the weakness of the US dollar in relation to the Euro, or to several other speculative reasons.

Therefore, it appears evident that we are now faced with making a choice that cannot be postponed, for it is necessary to take preventative action to avoid the start and/or exacerbation of dangerous economic and political crises. Measures that do not necessarily involve government intervention can be taken to counteract this trend: the reduction of energy consumption and energy waste, and the use of alternative sources and technologies (e.g. hydrogen in fuel cells) and/or renewable energies (solar, wind, geothermal, etc.) characterized by lower environmental impact.

Appendix A. Calculation of peak value and area for variant of the Hubbert curve

The peak production value of the variant of the Hubbert curve proposed in this paper can be obtained from Eq. (2), in which

$t = t_M$. Since $\cosh 0 = 1$, this provides

$$P_{\max} = \frac{2P_M}{1+k} \tag{A1}$$

The value of the area under this curve (which, in this specific case, represents the Ultimate) can be calculated as

$$U = 2\int_0^{t_M} \frac{2P_M}{1+k\cosh[b(t-t_M)]}\,dt = \frac{8P_M}{b}\,\frac{arctgh[\sqrt{(1-k)/(1+k)}tgh(bt_M/2)]}{\sqrt{1-k^2}} \tag{A2}$$

See details for calculation of the integral in Appendix B.

However, since $bt_M/2 \gg 1$, we have $\mathrm{tgh}(bt_M/2) \approx 1$; therefore, the previous relationship becomes

$$U = \frac{8P_M}{b}\,\frac{arctgh(\sqrt{(1-k)/(1+k)})}{\sqrt{1-k^2}} = \frac{4P_M}{b}\,\frac{\ln(1+\sqrt{1-k^2})-\ln(k)}{\sqrt{1-k^2}}, \qquad 0<k<1 \tag{A3}$$

where the last member is obtained by applying the known relationship $\mathrm{arctgh}(x) = (1/2)\ln((1+x)/(1-x))$ and algebraic manipulation.

From Eq. (A3), since

$$\lim_{k\to 1}\frac{\ln(1+\sqrt{1-k^2})-\ln(k)}{\sqrt{1-k^2}} = 2\lim_{k\to 1}\frac{arctgh(\sqrt{(1-k)/(1+k)})}{\sqrt{1-k^2}} = 1 \tag{A4}$$

then $U = 4P_M/b$, as expected, for the "classical" Hubbert curve ($k = 1$).

Appendix B. Calculation of the integral (A2)

The integral from Eq. (A2) is

$$2\int_0^{t_M} \frac{2P_M}{1+k\cosh[b(t-t_M)]}\,dt = 4P_M\int_0^{t_M} \frac{dt}{1+k\cosh[b(t-t_M)]} \tag{B1}$$

Based on known relationships for hyperbolic functions, we have

$$1+k\cosh(x) = 1+k\left[\frac{1+tgh^2(x/2)}{1-tgh^2(x/2)}\right] = \frac{1-tgh^2(x/2)+k[1+tgh^2(x/2)]}{1-tgh^2(x/2)} = \frac{(1+k)-(1-k)tgh^2(x/2)}{\mathrm{sech}^2(x/2)}$$

Therefore, the integral (B1) becomes

$$4P_M\int_0^{t_M} \frac{dt}{1+k\cosh[b(t-t_M)]} = 4P_M\int_0^{t_M} \frac{\mathrm{sech}^2[b(t-t_M)/2]}{(1+k)-(1-k)tgh^2[b(t-t_M)/2]}\,dt \tag{B2}$$

which can be solved by substituting $u = \mathrm{tgh}[b(t-t_M)/2]$, thus $du = (b/2)\mathrm{sech}^2[b(t-t_M)/2]dt$.

In fact, by considering the corresponding indefinite integral, we obtain

$$\int \frac{\mathrm{sech}^2[b(t-t_M)/2]}{(1+k)-(1-k)tgh^2[b(t-t_M)/2]}\,dt = \frac{2}{b}\int\frac{du}{(1+k)-(1-k)u^2} = \frac{2}{b(1-k)}\int\frac{du}{(1+k)/(1-k)-u^2} = \frac{2}{b(1-k)}\sqrt{\frac{1-k}{1+k}}arctgh\left(\sqrt{\frac{1-k}{1+k}}u\right) = \frac{2}{b\sqrt{1-k^2}}arctgh\left(\sqrt{\frac{1-k}{1+k}}tgh\left[\frac{b(t-t_M)}{2}\right]\right) \tag{B3}$$

in which the known integration formula $\int dx/(a^2-x^2) = (1/a)\mathrm{arctgh}(x/a)$ with $|x|<|a|$, has been applied.

By substituting (B3) in (B2), we find Eq. (A2)

$$4P_M\int_0^{t_M} \frac{\mathrm{sech}^2[b(t-t_M)/2]}{(1+k)-(1-k)tgh^2[b(t-t_M)/2]}\,dt = \frac{8P_M}{b\sqrt{1-k^2}}\left[arctgh\left(\sqrt{\frac{1-k}{1+k}}tgh\left[\frac{b(t-t_M)}{2}\right]\right)\right]_0^{t_M} = \frac{8P_M}{b\sqrt{1-k^2}}arctgh\left(\sqrt{\frac{1-k}{1+k}}tgh\left[\frac{bt_M}{2}\right]\right) \tag{B4}$$

being $\mathrm{tgh}0 = 0$, $\mathrm{arctgh}0 = 0$, $\mathrm{tgh}(-x) = -\mathrm{tgh}(x)$ and $\mathrm{arctgh}(-x) = -\mathrm{arctgh}(x)$.

References

Andrews, S., Udall, R., 2003. Oil Prophets: Looking at World Oil Studies over Time, ASPO Conference, Paris, May 26–27, 2003.

BP, 2008. BP Statistical Review of World Energy, June 2008. Available at: 〈http://www.bp.com/statisticalreview〉.

Brandt, A.R., 2007. Testing Hubbert. Energy Policy 35, 3074–3088.

Brown, L.R., 2008. Plan B 3.0: Mobilizing to Save Civilization. W.W. Norton & Company, New York. Available at: 〈http://www.earth-policy.org/Books/PB3/data.htm〉.

Campbell, C.J., 1996. The Twenty First Century: The World's Endowment of Conventional Oil and its Depletion, January 1996. Available at: 〈http://www.hubbertpeak.com/campbell/camfull.htm〉.

Campbell, C.J., 1997. The Coming Oil Crisis. Multi-Science Publishing Co. & Petroconsultants.

Campbell, C.J., 2002. Forecasting Global Oil Supply 2000–2050, Hubbert Center Newsletter #2002/3, Colorado School of Mines. Available at: 〈http://hubbert.mines.edu/news/Campbell_02-3.pdf〉.

CEC, 2007. Communication from the Commission to the Council and the European Parliament: Renewable Energy Roadmap, Renewable Energies in the 21st Century: Building a More Sustainable Future–COM (2006) 848, by Commission of the European Communities, January 10, 2007. Available at: 〈http://ec.europa.eu/energy/energy_policy/doc/03_renewable_energy_roadmap_en.pdf〉.

Cohen, D., 2009. Are We in the Post-peak Era?, February 19, 2009. Available at: 〈http://www.aspousa.org/index.php/2009/02/are-we-in-the-post-peak-era〉.

Duncan, R.C., Youngquist, W., 1998. The World Petroleum Life-Cycle, October 22, 1998. Available at: 〈http://dieoff.org/page133.htm〉.

EIA, 2006. World Consumption of Primary Energy by Energy Type and Selected Country Groups, 1980–2006. In: International Energy Annual 2006. Available at: 〈http://www.eia.doe.gov/pub/international/iealf/table18.xls〉.

EIA, 2007. World Crude Oil Production, 1960–2007. In: Annual Energy Review 2007, Report no. DOE/EIA-0384 (2007). Available at: 〈http://www.eia.doe.gov/emeu/aer/txt/stb1105.xls〉.

EIA, 2009a. Italy Energy Profile, updated on February 17, 2009. Available at: 〈http://tonto.eia.doe.gov/country/country_energy_data.cfm?fips=IT〉.

EIA, 2009b. World Oil Supply, 1970–2007. In: International Petroleum Monthly, January 2009. Available at: 〈http://www.eia.doe.gov/emeu/ipsr/t44.xls〉.

EIA, 2009c. World Natural Gas Plant Liquids Production, 1970–2007. In: International Petroleum Monthly, January 2009. Available at: 〈http://www.eia.doe.gov/emeu/ipsr/t43.xls〉.

EIA, 2009d. International Energy Outlook 2009, Report no. DOE/EIA-0484 (2009). Available at: 〈http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2009).pdf〉.

ENI, 2008. ENI World Oil and Gas Review 2008. Available at: 〈http://www.eni.it/wogr_2008/pdf/wogr2008-oil.pdf〉.

Foucher, S., (alias Khebab), 2008. Peak Oil Update–August 2008: Production Forecasts and EIA Oil Production Numbers. September 13, 2008. Available at: 〈http://www.theoildrum.com/node/3720〉.

Hirsch, R.L., Bezdek, R., Wendling, R., 2005. Peaking of World Oil Production: Impacts, Mitigation & Risk Management. Rep. DOE/NETL. February 2005. Available at: 〈http://www.netl.doe.gov/publications/others/pdf/oil_peaking_netl.pdf〉.
Hirsch, R.L., 2007. Peaking of World Oil Production: Recent Forecasts. Rep. DOE/NETL-2007/1263, February 5, 2007. Available at: 〈http://www.netl.doe.gov/energy-analyses/pubs/Peaking%20of%20World%20Oil%20Production%20-%20Recent%20Forecasts%20-%20NETL%20Re.pdf〉.
Holland, S.P., 2006. Modeling Peak Oil, March 27, 2006. Available at: 〈http://www.uncg.edu/bae/people/holland/research/Holland_Peak_Oil.pdf〉.
Hubbert, M.K., 1956. Nuclear Energy and the Fossil Fuels, American Petroleum Institute, Drilling and Production Practice. In: Proceedings of Spring Meeting. San Antonio, Texas, pp. 7–25.
Hutter, F., 2009. Peak Oil Depletion & Energy Issues—TrendLines URR Estimates 2009. Available at: 〈http://www.trendlines.ca/urrblogarchive.htm〉.
Koppelaar, R., 2009. ASPO Netherlands, Oilwatch Monthly, May 18, 2009. Available at: 〈http://www.peakoil.nl/wp-content/uploads/2009/05/2009_may_oilwatch_monthly.pdf〉.
Laherrère, J.H., 1990. Les Réserves d'Hydrocarbures—Du Quasi Certain au Quasi Improbable: Pourquoi une Telle Incertitude?, Bulletin d'Informations Pétroliéres no. 6629.
Laherrère, J.H., 1997. Multi-Hubbert Modeling, July 1997. Available at: 〈http://www.hubbertpeak.com/laherrere/multihub.htm〉.
Laherrère, J.H., 2000. Learn strengths, weaknesses to understand Hubbert curve. Oil and Gas Journal 98 (16), 63–76 On the web with the title: The Hubbert Curve: Its Strengths and Weaknesses (2000). Available at: 〈http://dieoff.org/page191.htm〉.
Laherrère, J.H., 2002a. Comments on the book: Hubbert's Peak: The Impending World Oil Shortage, January 6, 2002. Available at: 〈http://www.oilcrisis.com/laherrere/Deffeyes_comments.pdf〉.
Laherrère, J.H., 2002b. Modelling Future Liquids Production from Extrapolation of the Past and from Ultimates. International Workshop on Oil Depletion, Uppsala University, Sweden, May 23–24, 2002.
Laherrère, J.H., 2005. Peak Oil and Other Peaks, CERN (European Organization for Nuclear Research) meeting, October 3, 2005, Meyrin, Switzerland. Available at: 〈http://www.hubbertpeak.com/laherrere/CERN200510.pdf〉.
Laherrère, J.H., 2006. When Will Oil Production Decline Significantly? European Geosciences Union General Assembly, Vienna, Austria, April 2–7, 2006. Available at: 〈http://www.hubbertpeak.com/laherrere/EGUVienna2006.pdf〉.
Langfitt, F., 2008. Americans Using Less Gasoline, March 5, 2008. Available at: 〈http://www.npr.org/templates/story/story.php?storyId=87924270〉.
Lynch, M.C., 2003. The New Pessimism about Petroleum Resources: Debunking the Hubbert Model (and Hubbert Modelers). Minerals and Energy 18, 21–32.
Markham, V.D., 2008. US Population, Energy & Climate Change, by the Center for Environment & Population (CEP), September 2008. Available at: 〈http://www.cepnet.org/documents/USPopulationEnergyandClimateChangeReportCEP.pdf〉.
Masters, C.D., Attanasi, E.D. Root, D.H., 1994. World Petroleum Assessment and Analysis. In: Proceedings of the 14th World Petroleum Congress, Stavanger, Norway, May 29–June 1, 1994.
OECD, 2008. OECD Factbook 2008: Economic, Environmental and Social Statistics, Paris. ISBN 978-92-64-04054-0.
OECD/IEA, 1998. World Energy Outlook 1998, Paris. ISBN: 92-64-16185-6.
OECD/IEA, 2001. World Energy Outlook 2001, Paris. ISBN: 92-64-19658-7.
OECD/IEA, 2008a. World Energy Outlook 2008, Paris. ISBN: 978-92-64-04560-6.
OECD/IEA, 2008b. Energy Technology Perspective 2008. Scenarios & Strategies to 2050. Paris. ISBN 978-92-64-04142-4.
OPEC, 2008. 151st (Extraordinary) Meeting of the OPEC Conference. Oran, Algeria, December 17, 2008. Available at: 〈http://www.opec.org/opecna/Press%20Releases/2008/pr172008.htm〉.
Petit, X., 2003. The Myth of Oil Scarcity, December 2003. Available at: 〈http://www.sec.ou.edu/mee/pdf/Research%20Papers%2007/The%20Myth%20of%20Oil%20Scarcity_Petit.pdf〉.
Rehrl, T., Friedrich, R., 2006. Modelling long-term oil prices and extraction with Hubbert approach: The LOPEX model. Energy Policy 34 (15), 2413–2428.
USGS, 2000. USGS World Petroleum Assessment 2000. US Geological Survey Fact Sheet no. 062-03. Available at: 〈http://pubs.usgs.gov/dds/dds-060〉.
Witten, B., 2006. Evaluating Hubbert's Peak and Improvements?. Oil and War 2006. Available at: 〈http://srb.stanford.edu/nur/GP200A%20Papers/ben_witten_paper.pdf〉.