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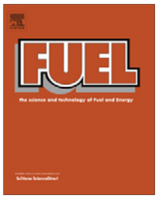

When will oil, natural gas, and coal peak?

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ABSTRACT

In this paper, a predictive model based on a variant of the multi-cyclic Hubbert approach is applied to forecast future trend in world fossil fuel production.

Starting from historical data on oil (crude and NGL), natural gas, and coal production, and taking into consideration three possible scenarios for the global Ultimate (i.e. cumulative production plus remaining reserves plus undiscovered resources), this approach allowed us to determine when these important energy sources should peak and start to decline. In particular, considering the most likely scenarios, our estimated peak values were: 30 Gb/year in 2015 for oil, 132 Tcf/year in 2035 for natural gas, and 4.5 Gtoe/year in 2052 for coal. A plateau is likely to occur in the case of natural gas, if the global Ultimate is high.

A comparison of the Multi-Hubbert Variant (MHV) approach used in this paper with both the Single-cycle Hubbert (SH) and the "original" Multi-cyclic Hubbert (MH) approach has also been done.

1. Introduction

According to EIA's International Energy Outlook 2010, total world primary energy consumption was 495 quadrillion Btu[1] in 2007 and is expected to increase by 49% from 2007 to 2035 [1].

Fossil fuels currently account for 86% of the primary energy demand (36% oil, 27% coal, and 23% natural gas), renewable sources (solar, wind, geothermal, biomass, hydroelectricity) account for about 8%, and nuclear power about 6% [2]. The US alone, with less than 5% of the world's population, relies on fossil fuels for 83% of its energy needs [3] and consumes about 25% of the world's energy supply [4].

Unfortunately, alternative energy sources are not free from disadvantages and limitations: renewable sources are constrained by their inherent intermittent nature and – in the case of solar and wind power systems – have high specific investment costs (per kW of installed capacity); nuclear power is almost exclusively used for electricity generation, which represents about one-third of the world's final energy consumption. Furthermore, public acceptance of nuclear plants is a critical issue and strongly depends on emotional factors: the recent Fukushima accident in Japan (2011) has reignited the debate about nuclear risks, 25 years after Chernobyl. New technologies based on other energy vectors like hydrogen (e.g. fuel cells) are still in the R&D stage.

Then, the importance of fossil fuels is unquestionable, but several negative aspects are either directly or indirectly related to their use. In particular, some prominent concerns are:

(a) environmental impact: carbon dioxide emissions due to the burning of fossil fuels are around 29 Gigatonnes per year [5], and it is estimated [6] that natural processes can only absorb around 40% of that amount;
(b) economic dependence on politically unstable countries or regions: about 56% of crude oil reserves and 41% of natural gas reserves are located in the Middle East [7];
(c) exhaustibility of fossil fuels: oil, gas, and coal are limited resources.

Several scientific approaches (logistic, Gaussian, Lorentz distributions, etc.), including asymmetric models (see e.g. [8,9]), have been used to predict future trend in fossil fuel production. In particular, many researchers and analysts focused their attention on the Hubbert peak theory with the aim of forecasting world and/or regional oil production [10–21]. Some papers made predictions for natural gas [22–26] or coal production [27–33]; but just a limited number of people centred on the ambitious objective of giving a comprehensive study including estimates for all fossil fuels [34–38].

In our previous paper [21], we proposed a variant of the well-known Hubbert curve and forecast a peak of world crude oil production (including natural gas liquids) between 2009 and 2021 at 29.3–32.1 Gb/year.

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[1] Based on EIA energy conversion tools (http://www.eia.gov/energyexplained/index.cfm?page=about_energy_conversion_calculator), 495 quad = 85.3 Gboe = 11.6 Gtoe = 486 EJ. BP 2011 [46] reports, for 2007, 11.4 Gtoe = 477 EJ = 83.6 Gboe = 452 quad for primary energy consumption. The discrepancy (about 10%) is due to different energy equivalences.

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The present work is an extension of the previous study. Specifically, in this paper we performed the following:

(a) Extension of the historical data (from 1950–2007 to 1857–2010) and update of the world oil production estimates presented in [21];
(b) Estimation of world natural gas and coal production;
(c) Comparison of the results obtained by the proposed Multi-Hubbert Variant (MHV) with those of the most common Single-Hubbert (SH) and Multi-Hubbert (MH) approaches.

2. Historical data and global Ultimate

Historical data on world fossil fuel (oil, natural gas, and coal) production and global Ultimate are essential input values for predictive models used in this context.

Please note we refer to oil production by considering the production of crude oil and natural gas liquids (NGLs). NGLs are hydrocarbons obtained from liquid fractions of natural gas and consist of natural gas plant liquids (NGPLs) and lease condensate (a mixture comprised of mainly pentanes and heavier hydrocarbons recovered as a liquid in lease separation facilities). Most producers include the condensate in the reported volume of crude oil production; then, the oil production we consider can be obtained as the sum of crude oil (including lease condensate) and NGPL.

2.1. Historical data on fossil fuel production

The following sources have been referenced for historical data on fossil fuel production.

2.1.1. Oil

Historical data on world crude oil production (including lease condensate) are taken from Ref. [39] for the period 1857–1959 and supplemented with data from the US Energy Information Administration (EIA) for the period 1960–1979 [40]. Historical data on world NGPL production are taken from Ref. [41] for the period 1920–1969 and integrated with EIA data for the period 1970–1979 [42]. Finally, the most recent data (1980–2010) on crude oil and NGPL production are taken from the EIA webpage on International Energy Statistics [43].

Oil production in this paper includes some unconventional oil sources. In fact, as reported in [44], EIA crude oil "may also include [...] liquid hydrocarbons produced from tar sands, gilsonite, and oil shale".

Based on EIA data [43], in 2010 world total oil supply amounted to about 86.8 Million barrels per day (74 Mb/d crude and condensate, 8.5 Mb/d NGPL, 2.2 Mb/d refinery processing gain, 2.1 Mb/d other liquids). Thus, the oil production to which we refer (crude plus NGL) represents about 95% of the present total supply.

2.1.2. Natural gas

Historical data on world natural gas production are taken from Ref. [45] for the period 1900–1979 and integrated with EIA data [43] for the period 1980–2010. In particular, EIA data on dry natural gas production – i.e. marketed production less extraction loss [44] in vented, flared and liquids conversion – are used in this paper.

2.1.3. Coal

Historical data on world coal production are taken from Ref. [33] for the period 1800–1980 and integrated with data from Beyond Petroleum (BP, formerly British Petroleum) for the period 1981–2010 [46].

2.2. Ultimate and scenarios

To quantify reserves and resources of fossil fuels (e.g. oil) the following synonyms are often used: "Estimated Ultimate Recovery" (EUR), "Ultimate Recoverable Resources" (URR), "Ultimate Recovery" (UR), or simply "Ultimate". These figures represent the total recovery from a field, which is the sum of past cumulative production, remaining 2P (proved plus probable) backdated reserves and undiscovered risked mean resources [47,48]. These concepts are not to be confused with the total amount of fossil fuel *initially-in-place* within the Earth, not all of which is recoverable [49].

Some values of fossil fuel global Ultimate can be found in the literature. Based on these estimates, the following scenarios have been considered.

2.2.1. Oil

World Energy Outlook 1998 [50] reported a range of 2100–2800 Gigabarrels (Gb) for oil Ultimate (i.e. ~290–380 Gtoe ~11 995–15 990 EJ), with an average value of 2300 Gb for crude oil only. A value of 3345 Gb for crude oil and NGL was reported in World Energy Outlook 2001 [51]. In World Energy Outlook 2008 [52], a value of 3577 Gb was given as ultimately recoverable conventional oil and NGL. These two last values are considered too high by several authors; in fact, most recent estimates for conventional oil fall in the range of 2000–3000 Gb (see [53,54]). In particular, Laherrère in [55–57] reported an Ultimate of 2250 Gb for crude oil (less extra-heavy) and NGL.

This figure was used as our reference lower limit scenario. The upper limit was fixed at 3000 Gb, in agreement with Laherrère's most recent estimate for crude oil and NGL (2200 Gb crude less extra-heavy, 500 Gb extra-heavy, 300 Gb NGL) [58]. A third intermediate scenario assuming an Ultimate of 2600 Gb has also been considered.

2.2.2. Natural gas

In [38,45], Laherrère considered an Ultimate of 10 000 Trillion Cubic Feet (Tcf) for conventional natural gas, a value estimated in 1996 [59]. A recent estimate, due to the same author [58], is 13 000 Tcf, including unconventional. According to Ref. [60], global gas Ultimate should fall between 9500 and 13 500 Tcf. The US Geological Survey suggested a global Ultimate in a range from 10 200 to 15 400 Tcf [60–62].

Based on these estimates, we assumed that world natural gas Ultimate ranges from a conservative 9500 Tcf to an optimistic 15 400 Tcf. A third intermediate scenario assuming a global gas Ultimate of 12 500 Tcf has also been considered.

2.2.3. Coal

As stated by Laherrère [63], the uncertainty on the world coal Ultimate is large, for the main coal producer China is difficult to forecast (unreliability of data), and the lack of consensus on a world coal classification (large range of heat content). He assumed a global Ultimate of 600 Gigatonnes of Oil Equivalent (Gtoe) in Ref. [38], recently updated to 750 Gtoe [63].

Nel and Cooper [35] reported that the current reserves plus cumulative production is 1126 Gt: a value estimated by the World Energy Council (WEC 2007) [64] as the sum of cumulative production at the end-2006 (about 280 Gt) and proved recoverable reserves of bituminous coal (including anthracite), sub-bituminous coal and lignite (847 Gt, altogether). This value was (almost) confirmed by WEC 2010 [33,65]: 1163 Gt. Since 1 toe of coal is equal to about 2 tonnes, these figures correspond to about 560–580 Gtoe.

Based on these estimates, we assumed that world coal Ultimate ranges from 550 Gtoe (pessimistic scenario) to 750 Gtoe (optimistic scenario). A third intermediate scenario assuming a global coal Ultimate of 650 Gtoe has also been considered.

3. Hubbert peak theory

In our previous paper [21], we presented a variant of the multicyclic Hubbert approach and determined the peak year and future trend in world oil production. In order to explain this, we need to recall some general aspects of the Hubbert theory.

3.1. Single-Hubbert (SH) approach

Geophysicist M.K. Hubbert (1903–1989) first proposed a general approach, now known as the "Hubbert peak theory", based on the observations that the supply of any resource is finite and that the production rate tends to increase exponentially during the initial phase of development, peak, and then decrease exponentially as the resource is depleted. In a groundbreaking paper [66] dated 1956, he applied this theory to crude oil production in the US Lower 48 states (i.e. all except Alaska and Hawaii, which joined the Union in 1959) and correctly predicted that it would peak as early as 1965 and no later than 1970.

Hubbert was rather vague about the mathematical formula he used to obtain his symmetric bell-shaped curve and claimed that his prediction made in 1956 was drawn by hand, although he seems to have favoured the derivative of the logistic function (originally derived by Verhulst) as the most appropriate model [67]. Then, the Hubbert curve is usually described by the following equation

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

where P is the oil production (at time t), P_M is the peak (maximum) production, b is a constant which accounts for the slope of the curve, and t_M is the peak year.

The area under the Hubbert curve is equal to

$$U = 4P_M/b \tag{2}$$

and represents the above-mentioned Ultimate.

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 from Eq. (2), once the value of Ultimate is fixed.

This approach is characterized by a single production cycle with a single peak. It is called here Single-Hubbert (SH) approach.

3.2. Multi-Hubbert (MH) approach

An interesting approach, characterized by several cycles and oil production peaks, is that proposed by Laherrère [11,12]. This approach is mentioned here as Multi-Hubbert (MH) approach.

The MH approach can be described by

$$P = \sum_{i=1}^{N} \frac{2P_{M_i}}{1 + \cosh[b_i(t - t_{M_i})]} \tag{3}$$

N being the number of cycles, P_{M_i} for $i = 1,\ldots, N$ the peak production of each cycle, and t_{M_i} the corresponding peak year.

A simple generalization of Eq. (2) provides the area under each production cycle

$$U_i = 4P_{M_i}/b_i \tag{4}$$

where b_i for $i = 1,\ldots, N$ are the slope of each cycle.

Using this approach, the number of fitting parameters is $2N$.

The Multi-Hubbert approach has already been used by some authors to estimate the production trend of oil [11,12,20], gas [22,23,38], and coal [31].

3.3. Multi-Hubbert Variant (MHV) approach

In our previous paper [21], the following variant of the Multi-Hubbert approach has been proposed:

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

which differs from the usual MH approach by the constant k_i ($0 < k_i \leqslant 1$, for $i = 1,\ldots, N$).

The maximum and the area under each Hubbert curve of this approach – mentioned here as Multi-Hubbert Variant (MHV) approach – are respectively (see Ref. [21] for details):

$$P_{\max_i} = \frac{2P_{M_i}}{1 + k_i} \tag{6}$$

$$U_i = \frac{4P_{M_i}}{b_i} \frac{\ln(1 + \sqrt{1 - k_i^2}) - \ln(k_i)}{\sqrt{1 - k_i^2}} \tag{7}$$

Both these formulas provide – as expected – maximum and area values corresponding to the "classic" Hubbert curve when the constant k_i tends to 1 [21]. Therefore, the MHV approach also includes both the usual Multi-Hubbert approach (when $k_i = 1$, for $i = 1,\ldots, N$) and the Single-Hubbert approach (when $N = 1$ and $k_1 = 1$).

Based on Eq. (5), the number of fitting parameters for the MHV approach is $3N$. However, excluding the occurrence of a cycle due to future (relevant) impact of oil and gas unconventional resources, we had been able to fit all the historical data on fossil fuel production with two Hubbert cycles. Thus, fitting parameters were reduced to five, because some preliminary evaluations showed that the value of one of the k_i constants always converged to 1 even if it was left free to vary [21].

A comparison between the three above presented Hubbert approaches (SH, MH and MHV) will be made in the next section.

4. Results and discussion

Results are shown in Figs. 1–16 and Tables 1–3. In particular, the following predictions were derived for each of the fossil fuels.

4.1. Oil

Historical data on world oil production (1857–2010, 154 values) were fitted with two Hubbert cycles. Ultimate U_1 of the first cycle was fixed at 150 Gb in agreement with Ref. [12]; therefore, Ultimate U_2 of the second cycle was determined as the difference between the global Ultimate ($U_{tot} = 2250 - 3000$ Gb) and U_1.

Fig. 1 refers to the most pessimistic scenario among those considered ($U_{tot} = 2250$ Gb), one in which the peak of the world oil production (crude and NGL) is about 29 Gb/year and has already occurred in 2009. Such a value is very close to the 2009 (actual) world oil production but is slightly lower than historical data for the period 2004–2010 (about 30 Gb/year, in 2010). If this scenario is assumed reliable, this disagreement can be justified by considering the fact that historical data on production from 2004 to 2010 (excluding the year 2009) could be interpreted as an anomalous rise, which might be followed by production values in line with the forecast curve again. As a partial confirmation of the forecast peak year (2009), some analysts believe the world has already entered in the "post-peak" (oil) era [68].

An opposite interpretation is also possible. The 2009 drop in oil production could be the effect of some contingent factors: in particular, the global economic recession which resulted in a decreased oil demand (e.g. US gasoline consumption fell by more than 3% from 2007 to 2008 [43]), and the OPEC members' decision

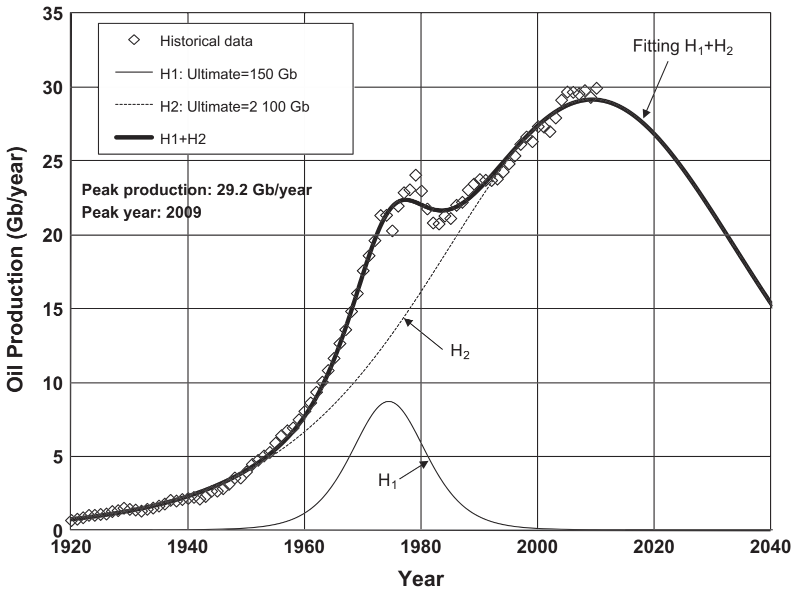

Fig. 1. World oil production calculated by MHV approach for a global Ultimate of 2250 Gb.

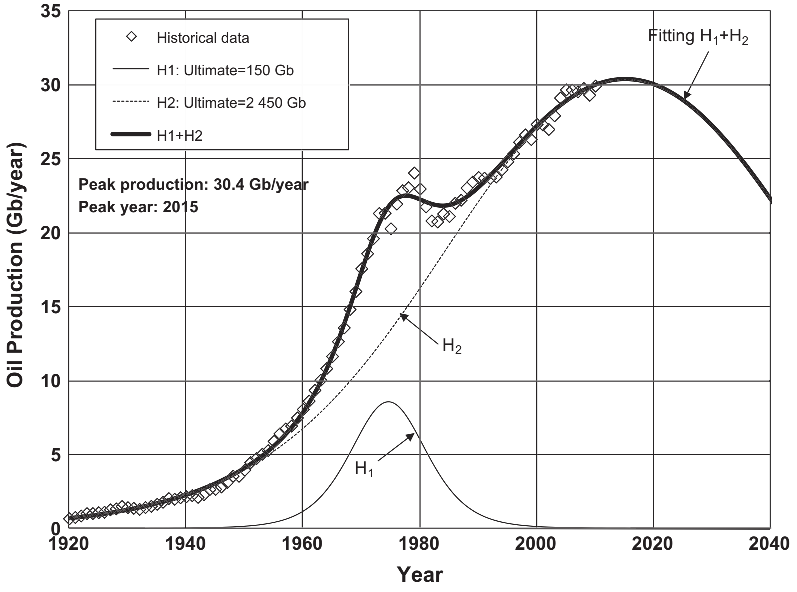

Fig. 2. World oil production calculated by MHV approach for a global Ultimate of 2600 Gb.

to slash their oil output [69]. In such a case, the estimates derived in our pessimistic scenario should be considered less reliable, and a scenario with an Ultimate higher than 2250 Gb would be more probable.

Results shown in Fig. 2 refer to the intermediate scenario with a global Ultimate of 2600 Gb. From this plot, it is evident that the peak of oil production would be about 30 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. 3, where oil production is forecast to peak in 2021 at about 32 Gb/year. In the two latter cases (Figs. 2 and 3) the model estimates fit very well with the historical data. In summary, from our analysis we conclude that within 10 years at most, the greater part of world oil production (crude oil and NGL) should reach its peak.

Fig. 4 and Table 1 show a comparison of the results obtained by the MHV approach. From Fig. 4 it can be observed how the peak value, peak year, and shape of the production curve change when the value of Ultimate ranges between 2250 and 3000 Gb. Table 1 reports all the values of the fitting parameters calculated for the three scenarios. The results in this table illustrate the following: the value of the constant k_2 decreases when the Ultimate increases, dropping from roughly 0.84 to 0.20 (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 estimates is always lower than 0.24 Gb/year, and the mean-square error (MSE) is lower than 0.38 Gb/year. Furthermore, the accuracy of the fitting is almost the same for the two scenarios with higher Ultimate – a relative standard deviation (RSD) equal to 2.3% has been calculated – and slightly better than that of the pessimistic scenario (2.5%).

Based on the intermediate scenario with a global Ultimate of 2600 Gb, a comparison of world oil production calculated by the three different model approaches (SH, MH and MHV) is shown in Fig. 5 and Table 1. As already mentioned, the peak obtained by

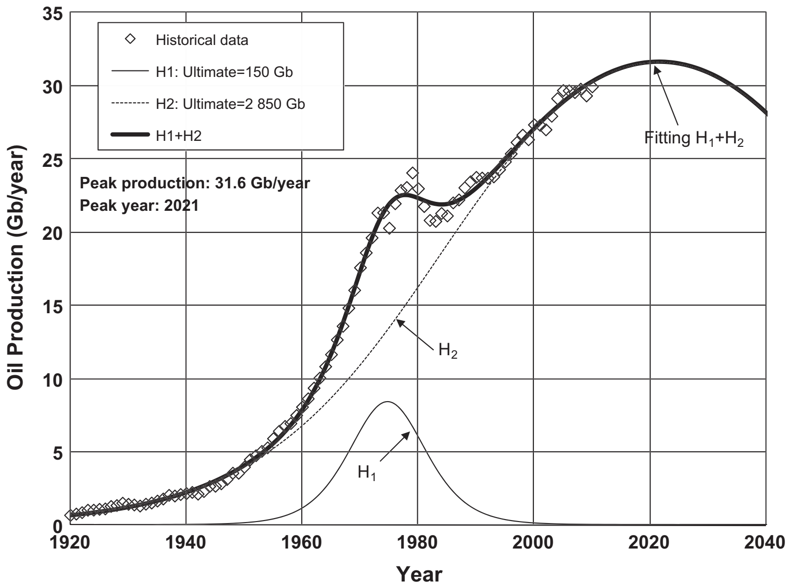

Fig. 3. World oil production calculated by MHV approach for a global Ultimate of 3000 Gb.

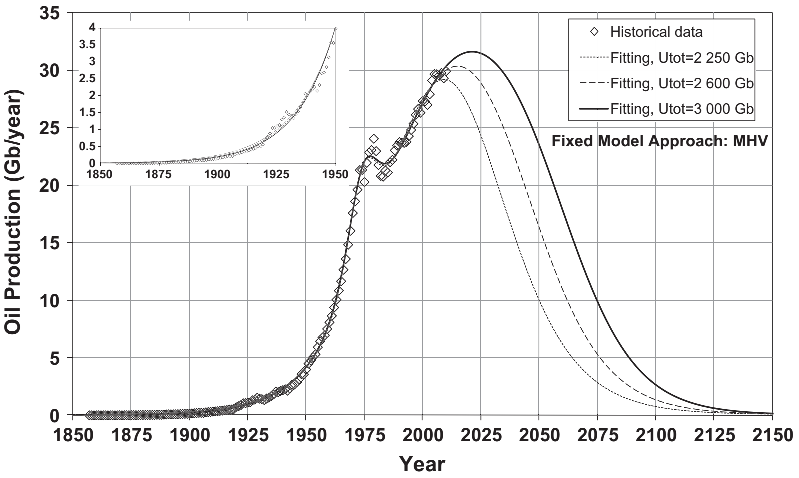

Fig. 4. Comparisons of world oil production calculated by MHV approach for a global Ultimate between 2250 and 3000 Gb.

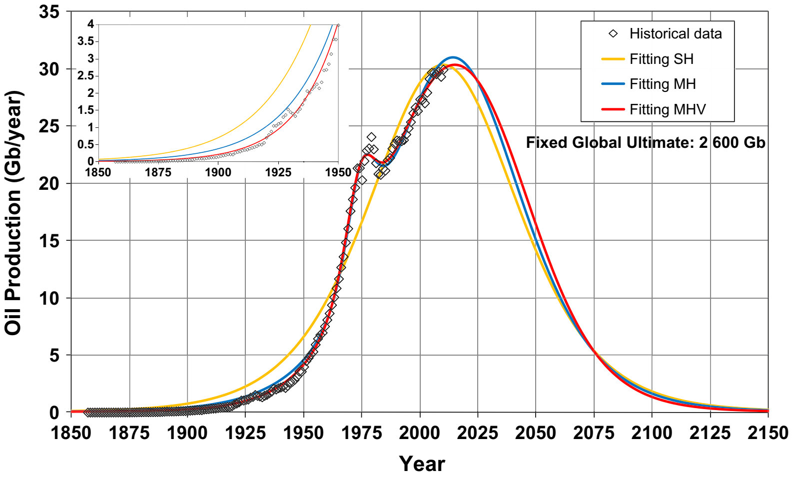

Fig. 5. Comparison of world oil production calculated by different model approaches for a global Ultimate of 2600 Gb.

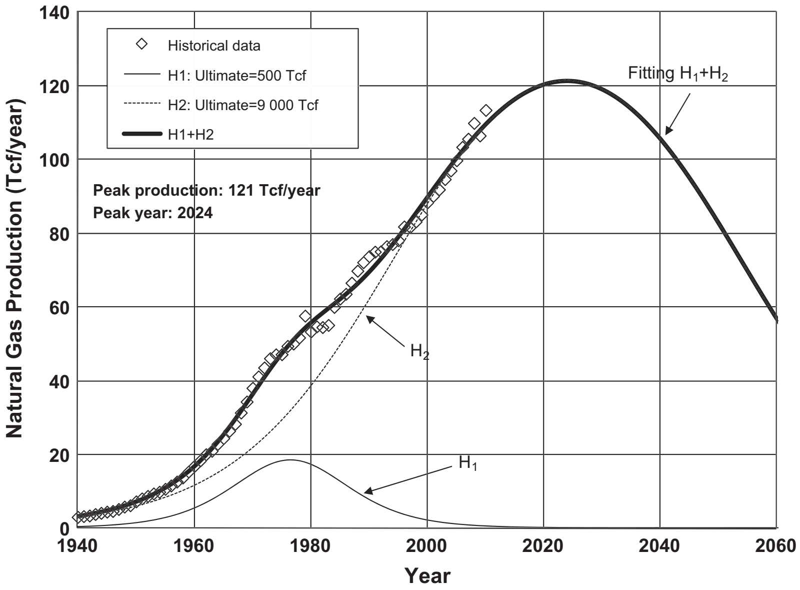

Fig. 6. World natural gas production calculated by MHV approach for a global Ultimate of 9500 Tcf.

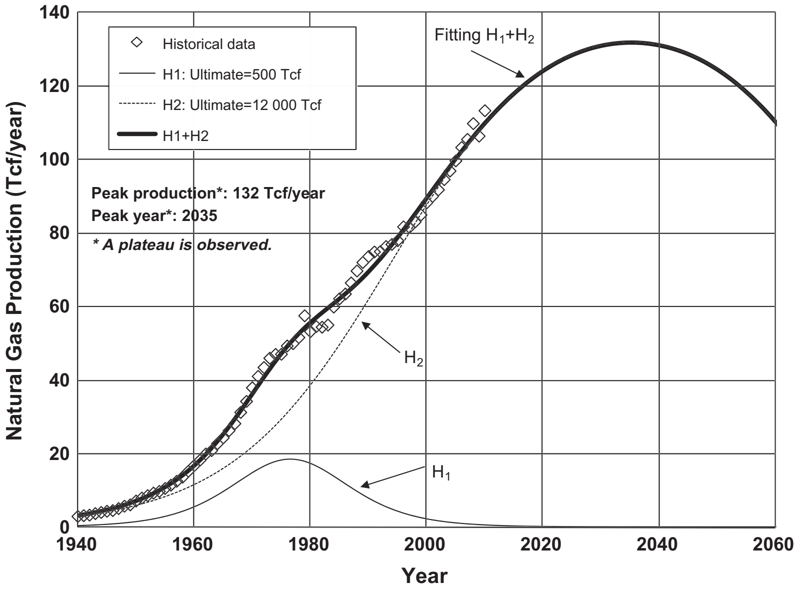

Fig. 7. World natural gas production calculated by MHV approach for a global Ultimate of 12,500 Tcf.

the MHV approach for the intermediate scenario was 30.4 Gb/year in 2015. The comparison showed that the peak production estimated by the SH approach is almost the same (30.3 Gb/year) but occurs five years early (2010); on the contrary, the peak year resulting from the MH approach (2014) is close to that calculated by the MHV approach, but the corresponding peak production is higher (31 Gb/year). In terms of accuracy, the MHV approach (RSD equal to 2.3%) is better than the usual MH approach (3.0%) and much better than the SH approach (11.8%).

The forecast oil peaks are in agreement with the literature data. Support for both peak production and peak year can be found in Refs. [54,70,71], which summarize dozens of estimates. In fact, world oil production is expected to peak between 2010 and 2030, but some of these estimates include oil from unconventional sources. For crude oil and NGL only, the calculated average of 20 estimates puts the peak year and peak production in 2012 and at 31.6 Gb/year respectively [70]. Furthermore, according to a comparison of estimates for all liquids [70], we should not expect a significant shift in the peak year due to unconventional oil sources.

Finally, it should be noted that the estimates obtained in our previous paper [21] are confirmed by this update (peak years between 2009 and 2021), with slight differences on the peak productions (29.3–32.1 Gb/year in Ref. [21], vs. 29.2–31.6 Gb/year in this paper).

Figs. 1–5 refer to crude oil plus NGL; some interesting forecasts which distinguish different type of oil (refinery gain, extra-heavy, NGPL, crude less extra-heavy, all liquids), leading to different peak dates and declines, can be found in Laherrère (see, e.g. [72]).

4.2. Natural gas

Analogously to the case of oil, historical data on world (dry) natural gas production (1900–2010, 111 values) were fitted with two

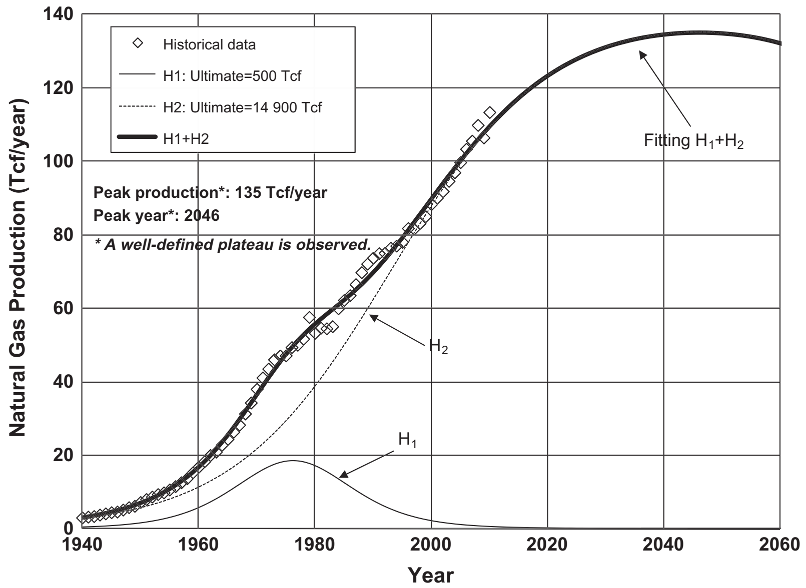

Fig. 8. World natural gas production calculated by MHV approach for a global Ultimate of 15 400 Tcf.

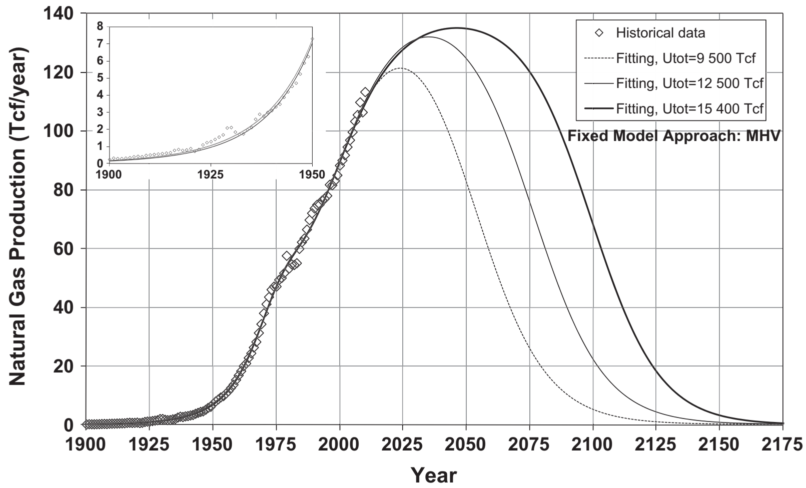

Fig. 9. Comparisons of world natural gas production calculated by MHV approach for a global Ultimate between 9500 and 15 400 Tcf.

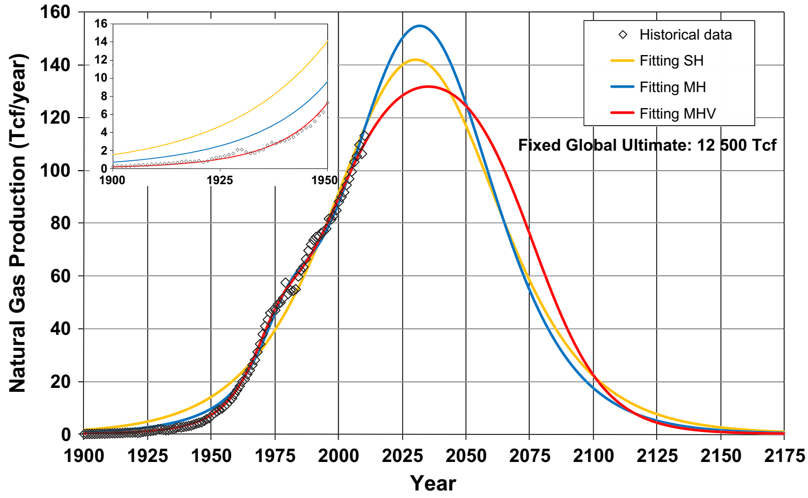

Fig. 10. Comparison of world natural gas production calculated by different model approaches for a global Ultimate of 12 500 Tcf.

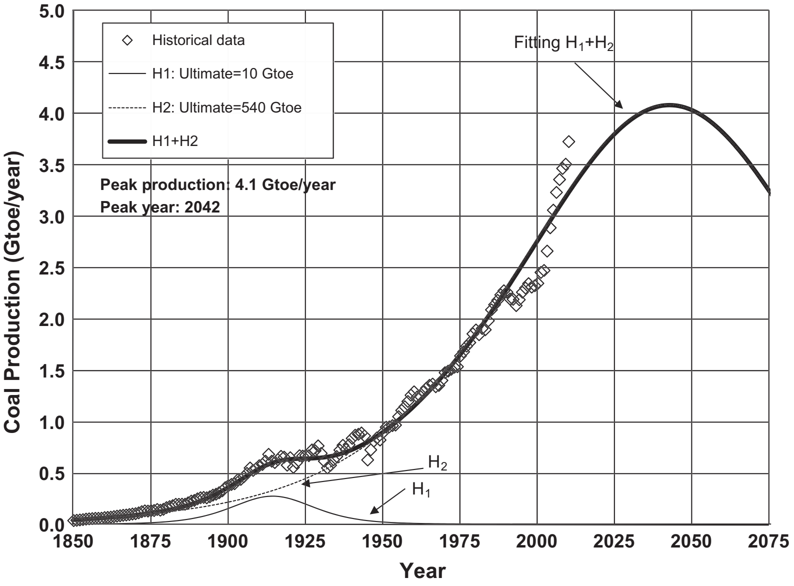

Fig. 11. World coal production calculated by MHV approach for a global Ultimate of 550 Gtoe.

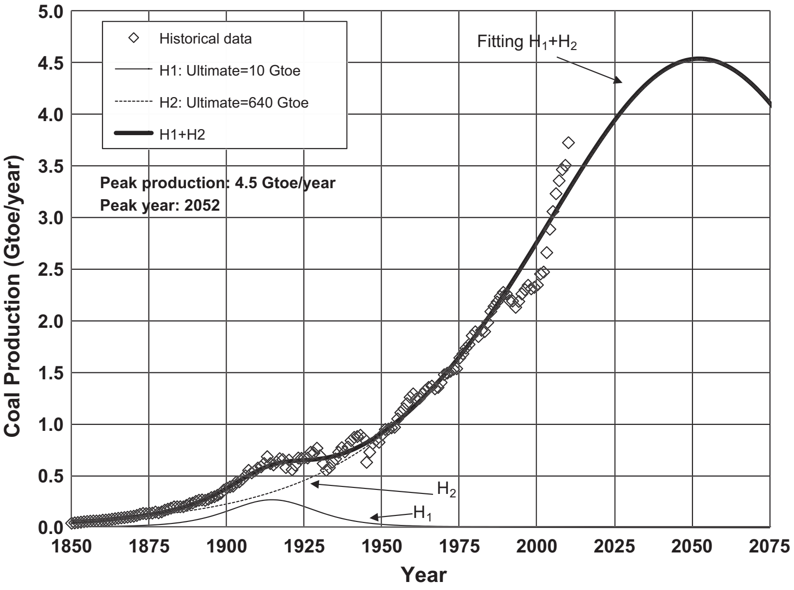

Fig. 12. World coal production calculated by MHV approach for a global Ultimate of 650 Gtoe.

Hubbert cycles. Ultimate of the first cycle was fixed at 500 Tcf in accordance with Ref. [38]; Ultimate of the second cycle was determined by deducting this value from the global Ultimate (9500–15 400 Tcf). Since the production reported by EIA includes non-conventional gas when the model does not, this may introduce discrepancy from the model with future EIA data.

Fig. 6 refers to the most pessimistic scenario among those considered (U_{tot} = 9500 Tcf) and shows that the natural gas peak production should be reached in 2024 at 121 Tcf/year, a value almost 7% higher than the 2010 actual world gas production. As results from Fig. 7, the gas production was forecast to peak around 2035 at about 132 Tcf/year, when referring to the intermediate scenario (12 500 Tcf of Ultimate). The peak is 135 Tcf/year for the scenario with a global Ultimate of 15 400 Tcf (Fig. 8), but in this latter case the estimates suggest a well-defined plateau (partly evident in the intermediate scenario, also) of production – less than 1% below the peak level, from 2037 to 2055 – rather than a sharp peak. In this regard, it can be evidenced that the occurrence of a future plateau has already been conjectured by some authors, both for oil and gas production [22,73–75]. A key advantage of our approach is that, differently from the classical Hubbert approach (or the multi-cyclic version), it is able to forecast the possible occurrence of a plateau. In summary, our analysis has led to the conclusion that world natural gas production should peak (or at least plateau) within the next 35–40 years.

Fig. 9 and Table 2 show a comparison of the results obtained by the MHV approach for a global Ultimate between 9500 and 15 400 Tcf. The values of the constant k_2 are very low (compared to the 1.0 in the classic Hubbert curve); in fact, they ranges from about 0.26 to 0.04 (see Table 2). In particular, values lower than 0.10 are the reason of the plateau. In terms of statistical errors, the following considerations can be made: MAE is always about

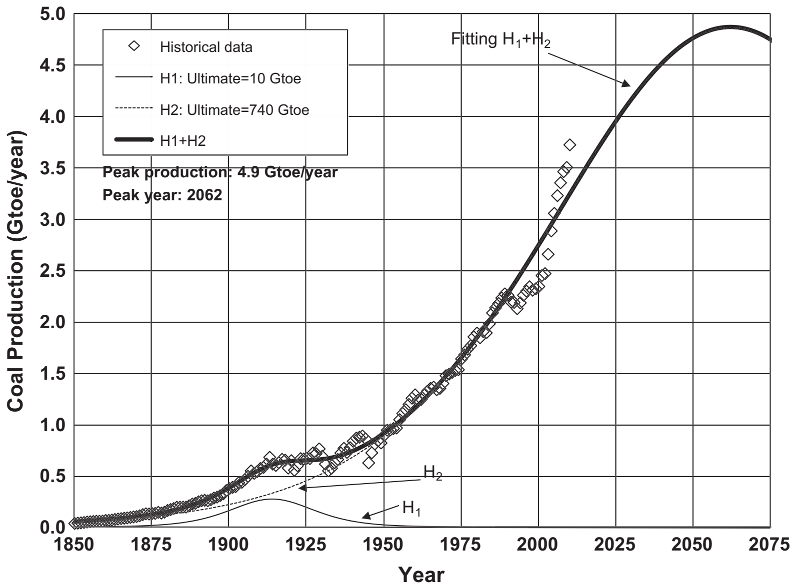

Fig. 13. World coal production calculated by MHV approach for a global Ultimate of 750 Gtoe.

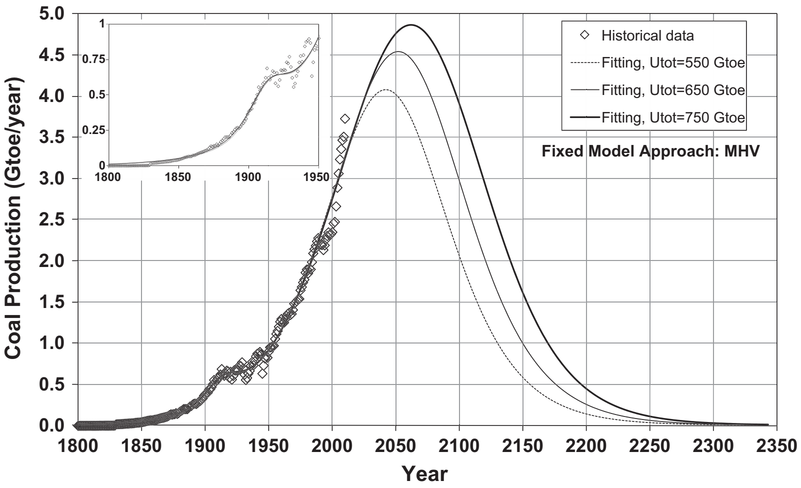

Fig. 14. Comparisons of world coal production calculated by MHV approach for a global Ultimate between 550 and 750 Gtoe.

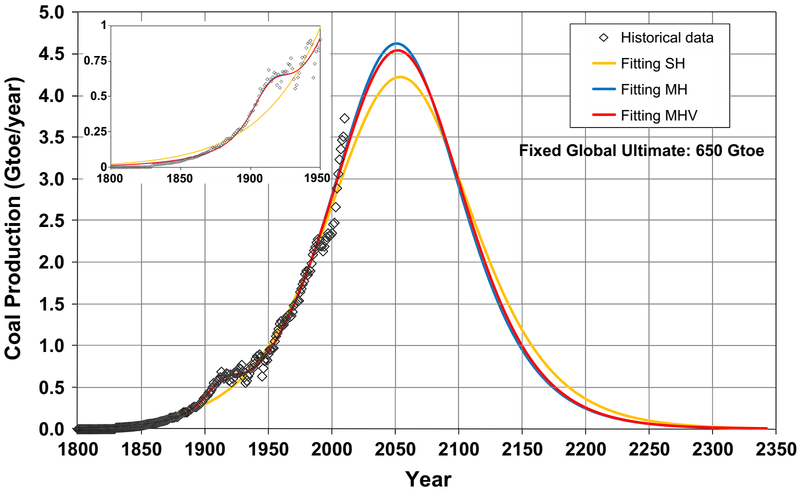

Fig. 15. Comparison of world coal production calculated by different model approaches for a global Ultimate of 650 Gtoe.

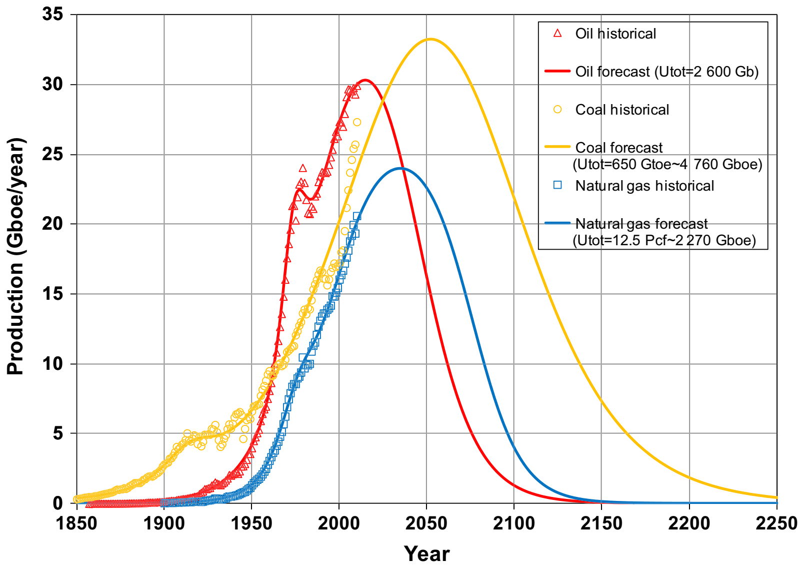

Fig. 16. Comparison of fossil fuel forecasts calculated for intermediate Ultimate scenarios.

Table 1
Fitting results for world oil production.

Parameter		Model approach				
		MHV	MHV	MHV	SH[a]	MH
Ultimates	U_1 (Gb)	150	150	150	–	150
	U_2 (Gb)	2100	2450	2850	2600	2450
	U_{tot} (Gb)	2250	2600	3000	2600	2600
Slopes	b_1	0.233	0.228	0.225	–	0.235
	b_2	0.057	0.060	0.062	0.047	0.051
MHV constants	k_1	1	1	1	–	1
	k_2	0.835	0.366	0.200	1	1
1st *Cycle peak production*	$P_{\max_1} = P_{M_1}$ (Gb/year)	8.7	8.5	8.5	–	8.8
1st *Cycle peak year*	t_{M_1}	1974	1975	1975	–	1975
2nd Cycle (apparent) peak production	P_{M_2} (Gb/year)	26.8	20.7	19.0	30.3	31.0
Peak production[b]	$P_{\max_2}$ (Gb/year)	29.2	30.4	31.6	30.3	31.0
Peak year[b]	t_{M_2}	2009	2015	2021	2010	2014
Errors[c]	MAE (Gb/year)	0.23	0.20	0.19	1.29	0.33
	MSE (Gb/year)	0.37	0.34	0.34	1.77	0.45
	RSD (%)	2.5	2.3	2.3	11.8	3.0

[a] For a better comparison, the single cycle of the SH approach has been virtually identified with the second cycle.
[b] Peak production and peak year coincide with those in the second Hubbert cycle, for the first cycle has already exhausted its effect.
[c] MAE = Mean Absolute Error; MSE = Mean-Square Error; RSD = Relative Standard Deviation.

0.90 Tcf/year, and MSE is lower than 1.45 Tcf/year. The accuracy of the fitting is almost the same for the three scenarios considered: RSD is 2.7%, independently from the value of the Ultimate.

Based on the intermediate scenario with a global Ultimate of 12 500 Tcf, a comparison of world gas production calculated by the three different approaches (SH, MH and MHV) is shown in Fig. 10 and Table 2. The comparison showed that the peak production estimated by the MHV approach (132 Tcf/year) is lower than the peak production corresponding to both the SH approach (142 Tcf/year) and the MH approach (155 Tcf/year) but should occur some years later (2035, vs. 2030 or 2032). In terms of accuracy, the MHV approach (RSD equal to 2.7%) is better than the usual MH approach (4.1%) and much better than the SH approach (9.1%).

Finally, the estimated gas peaks are in satisfactory agreement with the literature values: e.g. Valero and Valero [36,37] forecast the peak of natural gas in 2023; Jian et al. [75] estimated the peak of world conventional gas production at about 130 Tcf/year by the year 2030–2035; Laherrère [76] stated that natural gas should peak around 2020 at 110 Tcf/year (for a global Ultimate of 9000 Tcf) or around 2030 at 130 Tcf/year (for a global Ultimate of 12 000 Tcf, which includes 2000 Tcf for unconventional gas). This figure was afterwards updated to 2030 at about 140 Tcf/year in Ref. [38]. Some estimates are more conservative: e.g. Imam et al. [23] forecast the peak of natural gas at 88.43 Tcf/year in 2019.

4.3. Coal

Analogously to the two previous cases (oil and gas), historical data on world coal production (1800–2010, 211 values) were fitted with two Hubbert cycles. Ultimate of the first cycle was fixed and assumed to be 10 Gtoe; Ultimate of the second cycle was determined by deducting this value from the global Ultimate (550–750 Gtoe).

Table 2
Fitting results for world natural gas production[a].

Parameter		Model approach				
		MHV	MHV	MHV	SH	MH
Ultimates	U_1 (Tcf)	500	500	500	–	500
	U_2 (Tcf)	9000	12 000	14 900	12 500	12 000
	U_{tot} (Tcf)	9500	12 500	15 400	12 500	12 500
Slopes	b_1	0.149	0.147	0.148	–	0.150
	b_2	0.071	0.072	0.074	0.045	0.052
MHV constants	k_1	1	1	1	–	1
	k_2	0.263	0.106	0.040	1	1
1st *Cycle peak production*	$P_{\max_1} = P_{M_1}$ (Tcf/year)	18.6	18.4	18.4	–	18.8
1st *Cycle peak year*	t_{M_1}	1977	1977	1976	–	1980
2nd Cycle (apparent) peak production	P_{M_2} (Tcf/year)	77	73	70	142	155
Peak production	$P_{\max_2}$(Tcf/year)	121	132[b]	135[b]	142	155
Peak year	t_{M_2}	2024	2035[b]	2046[b]	2030	2032
Errors	MAE (Tcf/year)	0.90	0.89	0.90	4.32	1.74
	MSE (Tcf/year)	1.44	1.42	1.42	4.88	2.17
	RSD (%)	2.7	2.7	2.7	9.1	4.1

[a] See notes in Table 1.
[b] A plateau, rather than a sharp peak, is likely to occur (see Figs. 7 and 8).

Table 3
Fitting results for world coal production[a].

Parameter		Model approach				
		MHV	MHV	MHV	SH	MH
Ultimates	U_1 (Gtoe)	10	10	10	–	10
	U_2 (Gtoe)	540	640	740	650	640
	U_{tot} (Gtoe)	550	650	750	650	650
Slopes	b_1	0.112	0.107	0.110	–	0.109
	b_2	0.030	0.029	0.030	0.026	0.029
MHV constants	k_1	1	1	1	–	1
	k_2	1	0.825	0.540	1	1
1st *Cycle peak production*	$P_{\max_1} = P_{M_1}$ (Gtoe/year)	0.3	0.3	0.3	–	0.3
1st *Cycle peak year*	t_{M_1}	1915	1915	1914	–	1915
2nd Cycle (apparent) peak production	P_{M_2} (Gtoe/year)	4.1	4.1	3.7	4.2	4.6
Peak production	$P_{\max_2}$ (Gtoe/year)	4.1	4.5	4.9	4.2	4.6
Peak year	t_{M_2}	2042	2052	2062	2054	2051
Errors	MAE (Gtoe/year)	0.05	0.05	0.05	0.08	0.05
	MSE (Gtoe/year)	0.10	0.10	0.10	0.12	0.10
	RSD (%)	5.8	5.5	5.5	6.8	5.6

[a] See notes in Table 1.

Fig. 11 refers to our pessimistic scenario (U_{tot} = 550 Gtoe) and forecasts the world coal production peak in 2042 at 4.1 Gtoe/year, a value almost 9% higher than the 2010 real production. Based on the intermediate scenario (650 Gtoe of Ultimate), the peak should be shifted of a decade (2052) and becomes 4.5 Gtoe/year (Fig. 12); it could be further postponed by another decade (2062) if a global Ultimate of 750 Gtoe is assumed: in this latter case a peak production of 4.9 Gtoe/year has been predicted (Fig. 13). In summary, our analysis has led to the conclusion that world coal production should peak within about 50 years.

Fig. 14 and Table 3 show a comparison of the results obtained by the MHV approach for a global Ultimate between 550 and 750 Gtoe. As shown in Table 3, the values of the constant k_2 pass from 1.0 to 0.54 (a value of about 0.83 corresponds to the intermediate scenario); therefore, in the case of coal, a remarkable difference with the classic Hubbert curve can be observed only for the scenario with the highest value of Ultimate (750 Gtoe). In terms of statistical errors, the following considerations can be drawn: MAE is always 0.05 Gtoe/year, and MSE is always 0.10 Gtoe/year. The accuracy of the fitting is almost the same (RSD 5.5%) for the two scenarios with higher Ultimate (650–750 Gtoe) and slightly better than that calculated for the scenario with 550 Gtoe (5.8%).

The discrepancy between the forecast curves (Figs. 11–14) and the historical coal productions from 90' to early 2000's and for most recent years is related to a trough which seems to be due to constraints in China. Thus, the resulting fitting is also affected by these data, and the obtained curves are a "balance" between these values (which we preferred not to remove) and the others.

Based on the intermediate scenario with a global Ultimate of 650 Gtoe, a comparison of world coal production calculated by the three different approaches (SH, MH and MHV) is shown in Fig. 15 and Table 3. The comparison evidenced that, as a consequence of a k_2 value close to unity, the results of the two multi-cyclic approaches are almost identical (4.5 Gtoe/year in 2052 for MHV, vs. 4.6 Gtoe/year in 2051 for MH); while, the peak production estimated by the SH approach is lower (4.2 Gtoe/year) and cannot be significantly delayed (2054). In terms of accuracy, the MHV and

MH approaches are almost equivalent (RSD equal to about 5.6%) and (slightly) better than the SH approach (6.8%).

Finally, some support to coal peaks estimated in this study can be found in the literature: e.g. Valero and Valero [36,37] forecast the peak of world coal in 2060; based on the estimates made by Nel and Cooper [35,77,78], the global coal production should peak between 2048 at about 3.5 Gtoe/year (for an Ultimate of 1126 Gt∼560 Gtoe) and 2071 at about 5 Gtoe/year, but this last figure refers to a global coal Ultimate of ∼830 Gtoe (a peak production of about 4.3 Gtoe/year in 2061 was reported for an "average" Ultimate of ∼700 Gtoe); Laherrère [38,63] estimated that the world coal may peak around 2050 at 5.5 Gtoe/year (this figure is a bit higher than our best forecast: 4.9 Gtoe/year); Mohr and Evans [29] forecast a peak in 2034 at 157 EJ/year (i.e. ∼3.7 Gtoe/year; using the conversion 1 Gtoe = 41.868 EJ) for an Ultimate of ∼570 Gtoe, or in 2048 at 177 EJ/year (∼4.2 Gtoe/year) for an Ultimate of ∼620 Gtoe (this last estimate is in good agreement with our forecasts); according to Höök et al. [32] a global peak in coal production can be expected between 2020 and 2050; Zittel and Schindler [79] stated that "global coal production should peak around 2025 at 30% above present [i.e. 2007] production in the best case". This peak year (2025) is in disagreement with our forecasts (2042–2062), but the peak production calculated in our intermediate scenario is about 34% above 2007 production. Some analysts are more pessimistic: e.g. Patzek and Croft [31] predicted the global peak of coal close to the year 2011 at 160 EJ/year (∼3.8 Gtoe/year) for a global Ultimate of 13 200 EJ (∼315 Gtoe); Mohr and Evans [29] forecast a peak in 2010 at 145 EJ/year (∼3.5 Gtoe/year) for an Ultimate of 350 Gtoe; but these two estimates are affected by the values assumed for the Ultimate (too low, in our opinion).

A graph showing together oil, gas and coal forecasts – based on intermediate Ultimate scenarios (2600 Gb for oil, ∼2270 Gboe for gas, ∼4760 Gboe for coal) – is shown in Fig. 16.

5. Conclusion

In this paper, a variant of the Hubbert model – already introduced in our previous work [21] – has been used to estimate the peak production of fossil fuel production from historical data. This approach, mentioned as Multi-Hubbert Variant (MHV), has also been compared with the most used Single-cycle Hubbert (SH) approach and the usual Multi-cyclic Hubbert (MH) approach. In the case of MH and MHV approaches two production cycles have been considered.

The obtained results can be summarized as follows.

- World crude oil and NGL: assuming a global Ultimate in the range 2250–3000 Gb, the peak was estimated to be in the range 29.2–31.6 Gb/year and occurs between 2009 and 2021. These figures substantially confirm our previous estimates [21].
- World (dry) natural gas: assuming a global Ultimate in the range 9500–15 400 Tcf, the peak was estimated to be in the range 121–135 Tcf/year and occurs between 2024 and 2046. A plateau is likely to occur, especially for high values of Ultimate.
- World coal: assuming a global Ultimate in the range 550–750 Gtoe, the peak was estimated to be in the range 4.1–4.9 Gtoe/year and occurs between 2042 and 2062.

Thus, based on our estimates, all fossil fuels should peak within about the next half century (see Fig. 16).

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