Energy Research & Social Science 48 (2019) 257–261

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Peak oil, 20 years later: Failed prediction or useful insight?

Ugo Bardi

Dipartimento di Chimica, Università di Firenze, Polo Scientifico di Sesto Fiorentino, Sesto F., Fi, Italy

ARTICLE INFO

Keywords:
Peak oil
Oil depletion
Hubbert Model
System dynamics
Mineral resources
ASPO

ABSTRACT

20 years ago, in 1998, Scientific American published a paper by Colin J. Campbell and Jean H. Laherrère titled "The End of Cheap Oil" [1], starting a debate on oil depletion continuing to the present day. It was the return of a viewpoint on oil depletion which had been proposed more than 40 years before by Marion King Hubbert [2] and, in later years, largely forgotten. In their paper, Campbell and Laherrère updated Hubbert's model with new reserve estimates and proposed that the world's crude oil production would peak around 2004–2005, and then start an irreversible decline. Shortly afterward, Colin Campbell proposed the term "peak oil" for the highest global oil production level. The term was to become popular over the following decade, generating a true movement of ideas sometimes called the "peak oil movement." Today, these predictions turn out to have been only partially correct, mainly because the role of "non-conventional" oil was underestimated. The peak oil movement seems to have faded away, while the concept seems to have disappeared from the debate and to be commonly described has having been "wrong." The present paper reviews the cycle of the peak oil movement, examining how the peak oil concept was understood with the public and the decision makers and what caused its diffusion and its demise, at least up to the present time.

In March 1998, Scientific American published a paper titled "The End of Cheap Oil," [1] signed by two petroleum geologists, Colin Campbell and Jean Laherrère. It was a re-examination of a model developed for the first time by Marion King Hubbert in 1956 [2] which assumed that the oil production in a large geographical region follows a symmetric, bell-shaped curve. According to this interpretation, the peak production is reached when approximately half of the available oil resources are extracted. The concept was also occasionally referred to as the "oil mountain" [3] although the term "bell shaped curve" or "Hubbert Curve" remained always more popular. In 1956, Hubbert had applied his model to the United States, finding that production would peak around 1970. It turned out to be a correct prediction and the US production approximately followed the model until the early 2000s. Regarding the whole world, Hubbert proposed that the production of conventional oil would peak around the year 2000.

Hubbert's ideas had been largely forgotten in the 1990s as the result of the general optimism arising from the collapse in the oil prices of the second half of the 1980s. The low oil prices had convinced nearly everybody that oil depletion was not a problem for the foreseeable future but, in 1998, Campbell and Laherrère [1] updated Hubbert's predictions using the same "bell-shaped" model and updated estimates of the global oil reserves. Their results were broadly consistent with those obtained earlier on by Hubbert: according to the new estimate, the global oil production would peak approximately in 2004–2005 and then start an irreversible decline.

The paper by Campbelland Laherrère had a considerable international resonance and, in 2001, Campbell founded the "Association for the Study of Peak Oil and Gas" (ASPO) which collected scientists and experts interested in oil and energy matters. The association published a popular newsletter [4], mainly authored by Campbell himself, which appeared in 100 issues, the last one published in 2009 [5]. The term "peak oil" contained in the name of the association became well known and it generated much interest both on academic journals and on the mainstream media. ASPO's later estimates moved the peak some years forward, to around 2010, but that didn't change the interpretation based on the bell-shaped curve. In the discussion on the consequences of peak oil, it was generally agreed that the world would see a situation similar to that of the oil crisis of the 1970s: high oil prices, long lines at service stations, double digit inflation, and other negative effects. Some commentators went as far to predict that peak oil would generate the end of civilization as we know it. For general reviews on the subject of peak oil, see Sovacool et al. [6], Bentley et al. [7], Jacobsson et al. [8], Heinberg et al. [9], and Schneider-Mayerson [10].

Today, 20 years have passed since the publication of the groundbreaking Scientific American report [1]. The expected world peak has not arrived, at least in terms of a reduction of the global supply of liquid fuels [11] and, in general, the concept of peak oil has faded from the mainstream discussion as well as from the scientific literature. ASPO

E-mail address: ugo.bardi@unifi.it.

https://doi.org/10.1016/j.erss.2018.09.022
Received 27 March 2018; Received in revised form 20 September 2018; Accepted 27 September 2018
Available online 10 November 2018

international seems to have disappeared as an active association around 2012–2013, although some national branches of the association still exist. The generally accepted explanation for the fading interest in the concept attributes it to the "wrong predictions" of the date of the peak and, from there, most mainstream reports tend to define the whole concept as wrong and misleading (see e.g. the article by Luts in 2012 on Forbes [12]).

The present paper has the purpose of examining the cycle of the peak oil movement, mainly in terms of how the public and the policy makers react to assessments that we could define as "predictions of doom." The paper is organized as follows: first it examines how the peak oil model fared in predicting real world trends, then it examines how the popularity of the model surged and then declined, and, finally, discusses the reasons for the decline. The conclusion is that the decline of interest in peak oil is only marginally related to the validity of the concept as a predictive tool. Rather, it appears to be related to a "clash of absolutes" that sees the idea of decline caused by resource depletion incompatible with the current mainstream views of the economic system.

First of all, let's examine how the 'peakers' predictions fared over the past 20 years. Of course, there was no single prediction produced by people using the bell-shaped curve but, rather, a whole range of predictions, most of them seeing the global production peak to occur within the first 2–3 decades of the 21st century. In most cases, these models used as an input an assessment of the "ultimate recoverable resources" (URR), the total amount of oil that could be reasonably produced globally. The URR was determined by means of a combination of geological data and statistical methods aimed at obtaining reasonable estimates for areas for which no geological data were available. As obvious, the value of the URR for a certain region could be potentially affected by political considerations and, already in 1998, Campbell and Laherrére had noted suspiciously sharp increases in the reserves reported by some OPEC producing states [1]. In addition, they noted that new oil discoveries had not been matching production starting in the late 1980s, a phenomenon termed "the growing gap" and illustrated several times in the ASPO newsletter. This gap was considered as evidence that oil production was depleting the reserves faster than they could be replaced. An alternative approach was to use the historical data to determine the URR. In some cases, that was accomplished by means of the "Hubbert Linearization Method" [13].

In the simplest approach, used for instance by Deffeyes [14], the URR was one of the parameters of a model that fitted the historical production data with the derivative of a logistic function – the area under the curve was constrained to correspond to the URR. In other approaches, the expected lifetime curves of single production provinces were summed up in order to obtain a global curve – this was, for instance, the method used by Campbell and Lahèrrere [1,4]. In 1998 [1], they stated that the production of conventional oil would reach a maximum around 2005 at a level of about 74 million barrels per day and that, in any case, "the decline will begin before 2010." Later ASPO estimates updated the prediction and added "non-conventional" oil to the model. Fig. 1 shows the last forecast for the global production curve published on the ASPO newsletter in 2010. The peak for "regular oil" is supposed to appear in 2008. If other kinds of oil (heavy, polar, etc.) are included, the production peak appears later, around 2010, at about 80 million barrels/year. Estimates reported by other researchers placed the peak at later dates. For instance, a 2004 report by the Energy Information Administration (EIA) placed the peak within a range going from 2026 to 2047 [15]. Nevertheless, the predictions of the ASPO group remained at the center of the interest in the field.

An important problem, here, is what's to be intended exactly as "oil". In the oil industry, it is customary to class liquid hydrocarbons into two categories, "conventional" and "non-conventional." This classification has historical origins: in the early times of the industry all oil was referred to as "crude oil." Still today, crude and conventional oil are considered synonyms and are defined as "relatively light, flowable

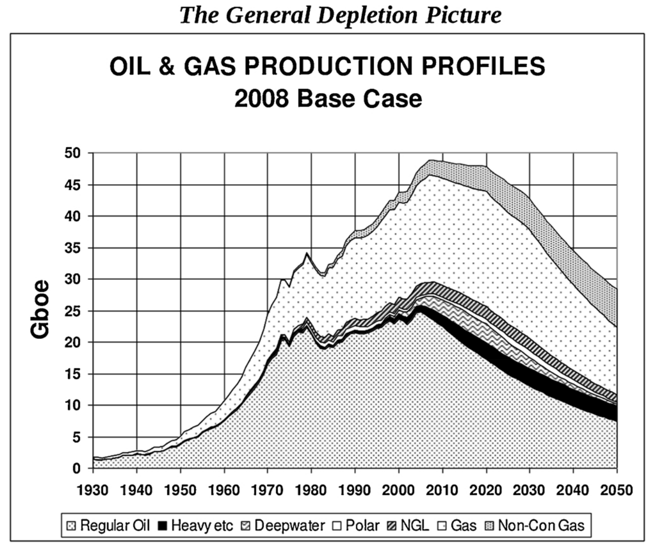

Fig. 1. The projection of oil production appearing in the 100th (and last) issue of the ASPO newsletter in 2009. It shows the peak for "regular oil" to appear around 2008, while the peak for "all liquids" (the sum of conventional and non-conventional oil) appears around 2010 [5].

oil found in fields" [7]. "Non-conventional" oil, instead, includes a wide range of substances, such as high density "heavy" oil, "deepwater oil", "polar oil," and everything that can be turned into a liquid fuel, from shale oil to the oil obtained from coal processing. Some of these liquids are not even fossil hydrocarbons, as it is the case for biofuels, sometimes added to the total. Then, the International Energy Agency (IEA) normally includes "refinery gains" in the total liquids production, that is, increases in volume resulting from a lower density of the final product. It should go without saying that these gains add nothing to the quantity of energy produced by a certain volume of oil.

The variety of types of oil adds a considerable complexity to the debate and it surely clouded the discussion on peak oil. In the text of their 1998 article, Campbell and Laherrere stated more than once that their prediction was for conventional oil only. But in the figure caption of the main graph of the article, the curve is described as referring to "both conventional and unconventional." According to Kjell Aleklett [16] this statement is an editorial intervention performed without the consensus of the authors but that's a further element of confusion in the story. In later issues of the ASPO newsletter, Campbell added the "non-conventional" category to his projections, but these new data didn't include some forms of liquids that would become important later on, such as shale oil. In general, it seems that most authors who were part of the peak oil movement tended to underestimate the role of non-conventional oil. For example, in the 2005 book, "Beyond Oil [13]," by Kenneth S. Deffeys, non-conventional oil sources are mentioned, but the conclusion is that (p. 108) these sources, "are not going forward on a scale large enough to postpone the Hubbert peak."

Having clarified, as much as possible, the methods and the assumptions used by the proponents of the peak oil idea, we can list the ASPO predictions over the 1998–2010 period as follows:

1 The world's oil production should follow a bell-shaped curve.
2 The global production peak of conventional oil should occur not later than 2010 at a level of the order of 70–75 million barrels per day (Mb/day).
3 The discoveries of new crude oil resources should remain well below consumption.
4 Oil prices should rise sharply.

Let's now examine how these predictions fared, one by one.

1. *The bell shaped production curve*. The examination of a large

number of productive regions confirms Hubbert's intuition that the bell-shaped production curve is a common feature, even though the curve is not necessarily symmetric. Brandt [17] found that in most historical cases production follows the curve, although the decline is slower than growth. It has been argued that the opposite could be true in the global case [18] or in cases of isolated systems [19]. However, in many cases, it was found that a single bell-shaped curve is not sufficient to describe the production cycle of a certain region. This is the case, for instance, of Russia and the US, where the decline after peaking was reversed by a new cycle of growth. In the case of the world's oil production, the bell curve is not clearly detectable today, but it could also be argued that peaking and declining are going to occur in the near future. Therefore, we can say that the result of this prediction is *correct*.

2. *Peak oil occurring before 2010 at no more than 75 Mb/day for conventional oil*. Considering conventional oil only, the IEA data indicate that production has been increasing slowly during the whole 21st century up to now, even though the phases of growth have been interrupted by periods of stasis. The current production is reported to be around 82 Mb/d [11,20,21], still slowly increasing. Some studies indicate that the global peak may be imminent [22,23], in this case we could say that the ASPO predictions were pessimistic, but not too far off the mark. On the contrary, if we consider "all liquids", Campbell (Fig. 3) predicted the peak around 2010 at about 82 Mb/day, while the available data indicates that the global production reached around 97 Mb/d11in 2017. On the basis of these data, we can say that the prediction of the peak date was *incorrect*.

3. *Discoveries not matching consumption*. By definition, this prediction can be applied only to regular (flowable) oil, since non-conventional resources, such as shale oil, do not normally need to be "discovered," their existence and location is known. Recent results have been reported by Bloomberg [24] on the basis of data from Rystad Energy (www.rystad.com), clearly indicating a large gap between discoveries and consumption which has been ongoing for at least two decades in the past. This prediction can be considered as *correct*.

4. *Rising prices*. The historical data (Fig. 2) show considerable oscillations but, clearly, the average price of oil has been rising after the turn of the century, in correspondence to the approaching of the production peak of conventional oil. So, this prediction can be considered as *correct*.

Overall, we can say that, even though the role of non-conventional oil sources was not correctly evaluated and the date of the peak missed at the global level, the Hubbert theory produced correct predictions

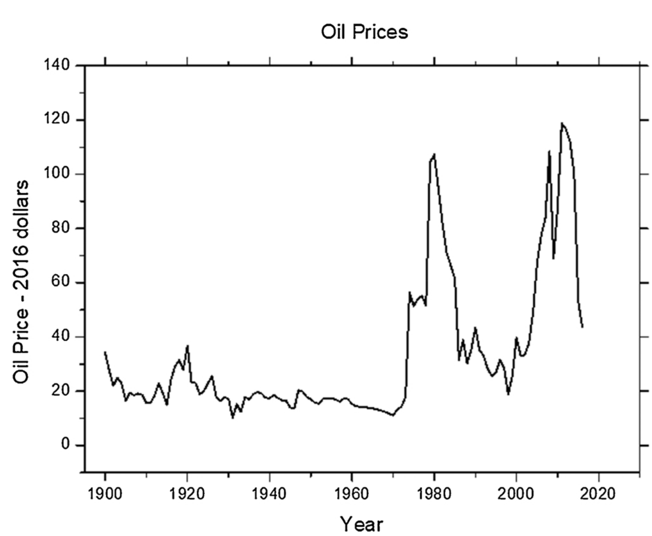

Fig. 2. Oil prices corrected for inflation and expressed in 2016 US dollars. 1900–1944 US Average, 1945–1983 Arabian Light posted at Ras Tanura. 1984–2016 Brent dated. $2016, deflated using the Consumer Price Index for the US. Data from BP.com.

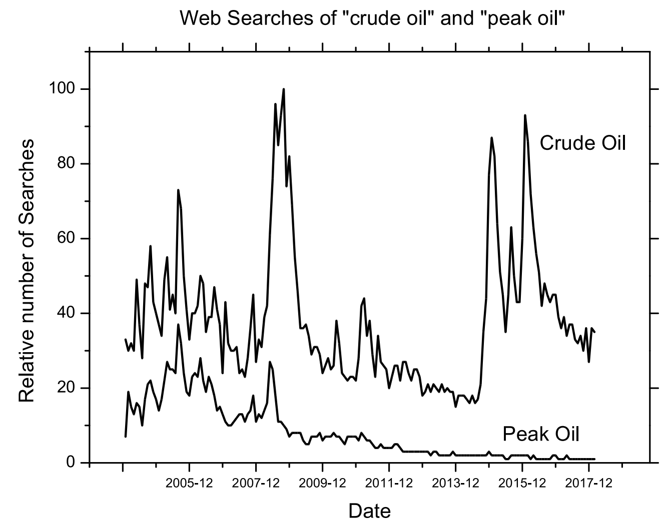

Fig. 3. Relative number of Web searches of the terms "peak oil" and "crude oil". Data from "Google Trends".

and, in general, a valuable warning of difficulties to come. So, there never were compelling reasons based on historical data to dismiss the peak oil idea as wrong or untenable. Nevertheless, this is what happened. The interest on peak oil in the mainstream debate can be quantified by means of data from "Google Trends" (https://trends.google.com/trends) which report the number of times that a certain term was searched for in the Google search engine (Fig. 3). The use of this tool as a reliable measurement method has been discussed and validated, for instance by Anderegg et al. [25], by Ortiz et al. [26], and Proulx et al. [27].

From the figure, we can see that searches of the "peak oil" term peaked at some moment in 2005, then gradually declined. This trend is confirmed by examining related terms, such as "oil depletion". The record oil prices reached in 2008 led to a temporary spike in interest but didn't change the overall trend. The curve shows a typical "viral" dissemination mechanism, that is, the interest in the concept grew by means of a positive reinforcing feedback [28]. Note, however, how the more generic term "crude oil" behaves differently, with the number of searches increasing again around 2014, apparently as a consequence of the collapse in the oil prices that started in that year.

In terms of academic research, a search using "Google Scholar" leads to the results shown in Fig. 4. In this case, the interest peaked around 2012, to decline afterward. Similar results were obtained from the data available on webofscience.com. Considering that an academic paper requires some time from its inception to its appearance in a journal, typically a few years, the timing of the decline of academic interest may be approximately the same as that of the mainstream debate.

Comparing these data with the predictions based on the peak oil theory, a point appears clear: the decline in interest started much before there were reasons to claim that the peak date had been missed and that, therefore, the predictions had been "wrong". The mainstream interest peaked in 2005, at least five years before the ASPO prediction for the peak (2010). Therefore, something else generated the decline.

A possible explanation may be searched in the weakness of the theoretical basis of the peak oil concept. Hubbert never proposed a theory that should have explained the reasons for the "bell shaped" curve [2]. In their 1998 paper, Campbell and Lahèrrere stated that "*Adding the output of fields of various sizes and ages usually yields a bell-shaped production curve for the region as a whole.*" That is an empirical description of the method they used, but hardly a theoretical model, but it has remained the standard one, even in recent times [7]. A specific problem, here, is that, if one assumes that the bell-shaped curve is the result of summing up the production curves of single fields, there

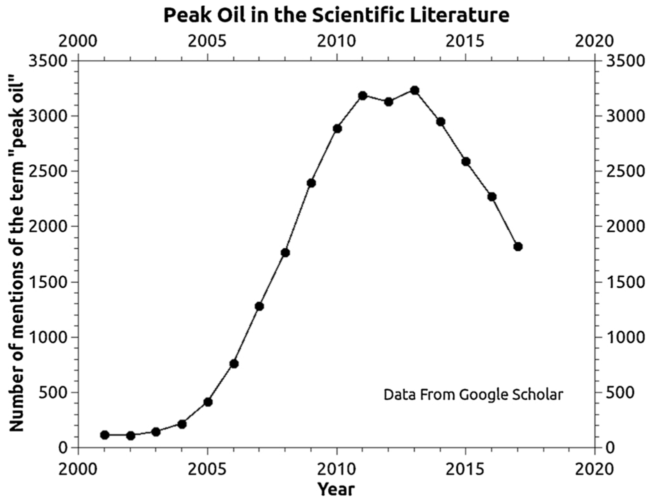

Fig. 4. Number of academic papers mentioning the term "peak oil." Data from "Google Scholar".

follows that it is determined mainly by geological factors. But, if it is geology that determines production, how is it that double or multiple production peaks are often observed? [29]. Consider the case of Russia. It has been argued that the increasing costs associated with peak oil were the main factor generating the political and economic collapse of the Soviet Union in 1991 [30,31]. But Russia inherited most of the oil resources of the former Union and then managed to start a new cycle of oil production. Clearly, he political collapse couldn't change the geology of the Russian territory and so other factors must have been at play. This weakness gave ammunition to the critics of the peak oil theory who tended to see the bell shaped curve as little more than a magic trick, not necessarily related to the real world (see e.g. the 2004 article by Leonardo Maugeri, eloquently titled "*Oil: never cry wolf – why the petroleum age is far from over*" [32]).

These were serious problems, but it must also be said that the weakness of the theory ceased to exist when it was understood that the bell shaped curve is just a simplified version of the general theory of mineral depletion [33] based on the concepts developed first by J. Forrester [34] and by the authors of the 1972 "Limits to Growth" report [35] (For a modern version of these models, see the recently developed MEDEAS model at www.medeas.eu). In short, the basis of the bell shaped curve is in the decline in the net energy of extraction, a concept often expressed in terms of "Energy Return On Energy Invested" (EROI or EROEI) [36,37]. So, the peak oil idea was based on solid theoretical foundations. The quote "when I have new data, I change my interpretation, what do you do, sir?" is attributed to John Maynard Keynes and one wonders why it was not applied to the peak oil theory. With new data in input on the consistency of the non-conventional oil resources, the theory could still provide useful information on the future of fossil fuels, but this was not done. Instead, most commentators preferring to engage in an activity that we could define as "Hubbert-bashing."

So, if we want to identify the causes of the decline of the peak oil idea, we must look at subtler elements which have to do with people's perception. A key factor in this assessment is the similarity with other predictive models which also produced pessimistic results. An example is that of climate change and global warming, studied by Anderegg and Goldsmith [25]. They found a continuous decline of interest starting in 2007, sporadically interrupted, but not changed, by events such as the "Climategate" episode of 2009. Clearly, there was no compelling evidence available in 2007 that could justify this decline – there is none even now. A similar cycle of interest could also be observed for the 1972 "The Limits to Growth" study [35]. As extensively discussed in [38], the decline started in the 1980s, well before the study could be said to have generated "wrong predictions" as it was commonly accused to have done.

These three cases – Peak Oil, Climate Change, and Limits to Growth – are related to each other and have in common the fact that the models on which they are based predict the unavoidable decline of the world's economy or, at least, the impossibility for it to keep growing for a long time. This view easily leads to a "doomerish" vision of the future and the peak oil movement tended to regard peak oil as an apocalyptic watershed for humankind, an interpretation surely not based on anything that the model in itself could support. Perhaps in agreement with this millenaristic attitude, the peak oil movement mostly failed to generate a political proposal. This point is well described by Schneider-Matherson [10] who shows how the members of the movement tended to prepare for the event in individual terms, emphasizing local and personal resilience. In some cases, they adopted or proposed a survivalist strategy, including stocking food, guns, and ammunition in expectation of the imminent collapse. Needless to say, this attitude didn't endear the movement to the mainstream decision makers.

We may therefore conclude that the peak oil predictions were considered incompatible with the commonly held views that see economic growth as always necessary and desirable and depletion/pollution as marginal phenomena that can be overcome by means of technological progress. That was the reason why the peak oil idea was abandoned, victim of a "clash of absolutes" with the mainstream view of the economic system. In the clash, peak oil turned out to be the loser, not because it was "wrong" but mainly because it was a minority opinion. The future will bring new data and, with them, the concept of peak oil might regain popularity for a second time, just as it did for the first time with the 1998 work of Campbell and Lahérrere.

References

[1] C.J. Campbell, J.F. Laherrere, The end of cheap oil, Sci. Am. (1998) 80–86.

[2] M.K. Hubbert, Nuclear energy and the fossil fuels, Spring Meeting of the Southern District (1956).

[3] P. Barnes, The Oil Mountain, Available at: (1993) https://www.oxfordenergy.org/wpcms/wp-content/uploads/2011/01/REV4-TheOilSupplyMountainIstheSummitinSight-PBarnes-1993.pdf.

[4] ASPO-Ireland Repository of ASPO Newsletters, (2018) Available at: https://aspoireland.wordpress.com/newsletter/newsletters-pdf/ Accessed: 27th February 2018.

[5] Campbell, C. ASPO Newsletter n. 100. (2009).

[6] B.K. Sovacool, M.A. Brown, S.V. Valentine, Energy resources and technology, Fact and Fiction in Global Energy Policy, John Hopkins University Press, 2016, pp. 83–101.

[7] R.W. Bentley, Introduction to Peak Oil, Springer -Lecture Notes in Energy, 2016.

[8] K. Jakobsson, R. Bentley, B. Söderbergh, K. Aleklett, The end of cheap oil: bottom-up economic and geologic modeling of aggregate oil production curves, Energy Policy 41 (2012) 860–870.

[9] R. Heinberg, "Peak Oil Demand" = Peak Oil - Resilience. Resilience, Available at: (2013) (Accessed: 21st March 2018), http://www.resilience.org/stories/2013-09-19/peak-oil-demand-peak-oil/.

[10] M. Schneider-Mayerson, Peak Oil: Apocalyptic Environmentalism and Libertarian Political Culture, Univ. of Chicago Press, 2015.

[11] International Energy Agency, Oil Market Report, Available at: (2018) Accessed: 17th February 2018 https://www.iea.org/oilmarketreport/omrpublic/.

[12] B. Lutz, Fulsome Fossil Fuels And The 'Peak Oil' Myth, (2018) Forbes Feb 6, 2012, https://www.forbes.com/sites/boblutz/2012/02/06/fulsome-fossil-fuels-and-the-peak-oil-myth/#b13770cc4f86 , accessed on Oct 01, 2018.

[13] K. Deffeyes, Beyond Oil. Hill and Wang, 2005.

[14] K. Deffeyes, Hubbert's Peak, the Impending World Oil Shortage, Princeton University Press, 2001.

[15] J.H. Wood, G.R. Long, D.F. Morehouse, Long-Term World Oil Supply Scenarios: the Future Is Neither As Bleak or Rosy As Some Assert, (2004).

[16] K. Aleklett, How Correct Were Colin Campbell and Jean Laherrère When They Published "The End of Cheap Oil" in 1998? Available at: (2018) (Accessed: 2nd March 2018), https://aleklett.wordpress.com/2015/02/26/how-correct-were-colin-campbell-and-jean-laherrere-when-they-published-the-end-of-cheap-oil-in-1998/.

[17] A.R. Brandt, Testing Hubbert, Energy Policy 35 (2007) 3074–3088.

[18] U. Bardi, The Seneca Effect. Why Growth Is Slow but Collapse Is Rapid, Springer Verlag, 2017.

[19] U. Bardi, The mineral economy: a model for the shape of oil production curves, Energy Policy 33 (2005).

[20] M. Mushalik, What Happened to Crude Oil Production after the First Peak in 2005? *Crudeoilpeak.info*, Available at: (2018) (Accessed: 18th September 2018), http://

crudeoilpeak.info/what-happened-to-crude-oil-production-after-the-first-peak-in-2005.
[21] A. Berman, The Miracle of Shale Gas & Tight Oil Is Easy Money Part I - Art Berman. Art Berman Web Site, Available at: (2016) (Accessed: 23rd August 2018), http://www.artberman.com/the-miracle-of-shale-gas-tight-oil-is-easy-money-part-i/.
[22] J.L. Hallock, W. Wu, C.A.S. Hall, M. Jefferson, Forecasting the limits to the availability and diversity of global conventional oil supply: validation, Energy 64 (2014) 130–153.
[23] S.H. Mohr, J. Wang, G. Ellem, J. Ward, D. Giurco, Projection of world fossil fuels by country, Fuel 141 (2015) 120–135.
[24] M. Holter, No Title, Available at: (2016) (Accessed: 18th November 2016), http://www.bloomberg.com/news/articles/2016-08-29/oil-discoveries-at-a-70-year-low-signal-a-supply-shortfall-ahead.
[25] W.R.L. Anderegg, G.R. Goldsmith, Public interest in climate change over the past decade and the effects of the 'climategate' media event, Environ. Res. Lett. 9 (2014) 054005.
[26] J.R. Ortiz, et al., Monitoring influenza activity in the United States: a comparison of traditional surveillance systems with google flu trends, PLoS One 6 (2011) e18687.
[27] R. Proulx, P. Massicotte, M. Pépino, Googling trends in conservation biology, Conserv. Biol. 28 (2014) 44–51.
[28] I. Perissi, S. Falsini, U. Bardi, Mechanisms of meme propagation in the mediasphere: a system dynamics model, Kybernetes (2018) In Press.
[29] I.S. Nashawi, A. Malallah, M. Al-bisharah, Forecasting world crude oil production using multicyclic Hubbert model, Energy Fuels 24 (2010) 1788–1800.
[30] D. Reynolds, M. Kolodziej, Former Soviet Union oil production and GDP decline: granger causality and the multi-cycle Hubbert curve, Energy Econ. 30 (2) (2008) 271–289 February 200830(2).
[31] D.B. Reynolds, Cold War Energy: The Rise and Fall of the Soviet Union, LLC, Alaska Chena, 2016.
[32] L. Maugeri, Science and industry. Oil: never cry wolf–why the petroleum age is far from over, Science (80-.) 304 (2004) 1114–1115.
[33] U. Bardi, A. Lavacchi, A simple interpretation of Hubbert's model of resource exploitation, Energies 2 (2009) 646–661.
[34] J. Forrester, World Dynamics, Wright-Allen Press, 1971.
[35] D.H. Meadows, D.L. Meadows, J. Randers, W.I. Bherens, The Limits to Growth, Universe Books, 1972.
[36] C.A. Hall, C.J. Cleveland, R. Kaufmann, Energy and Resource Quality: The Ecology of the Economic Process, Wiley Interscience, 1986.
[37] D.J. Murphy, C.A.S. Hall, Energy return on investment, peak oil, and the end of economic growth, Ann. N. Y. Acad. Sci. 1219 (2011) 52–72.
[38] U. Bardi, The Limits to Growth Revisited, Springer, 2011.