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ORIGINAL PAPER

The Resource-Limited Plateau in Global Conventional Oil Production: Analysis and Consequences

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Abstract

This paper describes the mechanism that drives the peak of conventional oil in a region, and shows that identifying this peak is assisted by access to oil industry backdated proved-plus-probable oil discovery data. The paper then uses estimates of the ultimately recoverable resource (URR) of conventional oil to show that the plateau in the global production of this oil since 2005 has been *resource-limited*, at least for oil prices well in excess of $100/bbl. Since this date the world's marginal barrels have been of non-conventional oils and 'other liquids'. The economic and political consequences of this plateau are then examined. These include the steep rise in oil price after 2004 (in significant part reflecting the increased production cost of the marginal barrels); this contributing to the 2008/9 global recession; the lower EROI ratios and higher CO_2 emissions of the marginal barrels; and the growth of US tight oil. The post-2004 oil price rise is set in the context of oil price changes since 1923. This shows that the price of oil over this period has been set primarily by increases in the marginal production cost of oil, overlain by relatively short-term price excursions due to supply/demand imbalances. Finally we note that the global economy as currently configured requires increasing supply of inexpensive oil if the economic expectations of the world's rapidly growing population are to be met. But supply of low-cost oil is in decline, and the world must use less oil to meet climate change goals. Resolving this conundrum looks to be difficult. Annex 1 sets out definitions and data. Annex 2 summarises the current wide range of views and forecasts of global 'all-liquids' supply.

Keywords Peak oil · Oil supply · Oil price · Resource limits

Introduction

Until recently the term 'peak oil' has meant the point in time at which oil production in a region, or the world as whole, reaches maximum and goes into decline due to *resource limits*. These limits can be simply not enough recoverable oil available in the region, but can also reflect a technical inability to produce this oil at a sufficient rate, or at a cost low enough for current economic structures to bear without significant reduction in the demand for oil.

However, the term has also now come to mean the point at which *demand* for oil in a region declines for reasons *not related* to oil supply limits (or to high oil prices that result from such limits). Such a 'demand peak' might result from city dwellers purchasing fewer cars, or from increased use of alternative fuels to power transport. In these cases the reduced demand for oil derives from social changes, including climate change considerations, rather than from physical limits to oil supply.

In recent years attention to resource-limited oil production peaks has diminished due to the increased production of 'light-tight' (shale) oil. But here we show that the importance of resource limits in understanding global oil production has not gone away; and specifically that since 2005 the world has reached its resource-limited plateau in the global production of conventional oil, at least for oil prices up to

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well in excess of $100/bbl. (See Annex 1 for the definition of conventional oil.)

Section 2 describes the methodology used to determine the peak in production of conventional oil in a region, while Sect. 3 examines the current global production plateau of this oil in more detail. Section 4 looks at some of the consequences of this plateau, including the high oil price that resulted. Section 5 sets this price increase in the context of historical oil prices, and analyses the main drivers of oil price change. Section 6 concludes.

Methodology

This section sets out the methodology used in this paper to analyse the resource-limited peak of conventional oil production in a region; greater detail is given in Bentley (2016a).

Mechanism of Peak Production

The mechanism that drives the resource-limited peak of conventional oil production in a region has long been well understood, see for example Hubbert (1956, 1982), Campbell and Laherrère (1998) and Sorrell (2009), and is as follows:

Almost all conventional oil producing regions are endowed with a significant number of discrete oil fields, but where the bulk of the oil is in a relatively small number of large fields. Because these fields are large, they are easier to find and more profitable to exploit, so generally get into production first. However, fairly soon these large fields see their production decline from some combination of the physical processes of loss of pressure, reduction in oil column, and increasing drive-fluid cut. The *resource-limited* peak in oil production in the region then occurs when the sum of the production declines from these large early fields becomes greater than the sum of production increases from the smaller, later fields. If oil discovery and production in the region are plotted on a cumulative basis, after some time both curves tend towards an asymptote that often indicates the region's ultimate recoverable resource of oil, its URR.

Peak at Approximately 'Mid-Point' of URR

Knowledge of whether the resource-limited peak of conventional oil production in a region is already past, or still in the future, cannot in general be determined by normal examination of the oil parameters for a region, including past production, current reserves, new discoveries or scope for technical gain. As a result analysts have often been taken by surprise by the occurrence of resource-limited oil production peaks; those of the US in 1970, Indonesia in 1977 and the UK in 1999 being examples. There are however a number of reliable ways to determine when such a peak will occur, as set out for example in Hubbert (1982), Campbell and Laherrère (1998), Campbell (2013), and Bentley (2016a).

The method used in this paper is the 'rule-of-thumb' that the peak of conventional oil production in a region occurs when about half the region's estimated ultimately recoverable resource of this oil (its conventional oil URR) has been produced, the so-called 'mid-point' rule. This rule has solid theoretical and empirical underpinnings (see Bentley 2016a), but of course is only an approximation.

If a region has relatively few oil fields, such as Austria or Bahrain, then the resource-limited production peak of conventional oil generally comes well before 50% of URR. But most regions with a significant number of fields peak around 50% (typically a bit before, see Sorrell et al. 2009); while modelling suggests that regions where giant fields have been held on-plateau for many years because of quotas may see their conventional oil production come off plateau somewhat after 50%.

For the world as a whole with its variety of regions, and where there have been constraints on production including prorationing and quotas, and on demand when too high an oil price led to demand destruction, the rule is probably even more approximate. But the rule's fundamental driver for conventional oil of the decline in production of large early fields not being compensated after peak by production from the many smaller later fields is little in doubt.

Note that once oil discovery in a region is well into decline, a detailed forecast of oil production in the region is often best done 'bottom-up' by field (or by project in the case of non-conventional oils). However, such modelling has its own problems of data availability and correctness of assumptions, and thus in the analysis below we are content to use the mid-point rule because of its simplicity and robustness.

The Need to Use Oil Industry Proved-Plus-Probable ('2P') Data, Not Public-Domain Proved ('1P') Oil Data

Use of the mid-point rule for conventional oil requires an estimate of the region's ultimately recoverable resource of this class of oil, its conventional oil URR (and see the components of this in 'Definition of URR' in Annex 1). In estimating URR a major problem arises because there are two very different types of oil reserves data. The first and most commonly quoted type is the proved (1P) reserves. However, these data suffer from generally being underestimates of the true reserves; in some case are probably significant over-estimates (particularly for some large Middle East oil producers); and frequently the data are not updated, sometimes not for decades, see, e.g. Bentley et al. (2007) and Bentley (2018).

By contrast, a region's proved-plus-probable (2P) oil reserves estimate the 'most-likely' quantity of reserves in the region. However, these data are often hard to access, or else available but at a high price from oil consultancies. For a more detailed discussion of oil reserves see Annex 1, and Laherrère et al. (2016, 2017).

In this paper use is made of URR estimates based on oil industry 2P data including those from Campbell (2013), IHS Energy (Miller and Sorrell 2014), Globalshift Ltd. (2018), and Rystad Energy (2018, 2019, 2020).

The Global Resource-Limited Plateau in Conventional Oil Production

As mentioned earlier, the aim of this paper is to understand the resource-limited plateau in the global production of conventional oil. This in turn requires knowledge of three supporting concepts: the definition of conventional oil; recognition that the world still contains large quantities of oil (and of other sources that can be turned into oil), but that only a small part of this is conventional oil; and how fast, and when, conventional oil has been discovered. The first two ideas are discussed in Annex 1; in the following section we look at the rate of global conventional oil discovery over time.

History of Oil Discovery

Because conventional oil occurs in oil fields, these first need *discovering* through some combination of geological knowledge, exploration, investment and luck. By contrast for the non-conventional oils and other liquids their sources were often recognised long in the past, but they only come to market once adequate production technology has been developed, and the price of oil sufficiently high.

Figure 1 shows the history of the world's discovery of oil on a cumulative basis, which plots IHS Energy backdated 2P discovery data for all-oil plus condensate, excluding natural gas plant liquids (NGPLs).

As Fig. 1 shows, for many years from at least the 1920s global discovery of oil raced ahead of production, putting oil 'in the bank' in the form of 2P reserves. But the rate of global oil discovery peaked in the mid-1960s, once much of the large quantities of oil discovered by digital seismic were in; and where this discovery peak is visible in the figure as the inflection point in the cumulative discovery curve. Subsequently global discovery of oil slowed, and around 1980 the annual rate of discovery was caught up by the rapidly increasing annual production of oil, with the result that after around 1980 the global 2P reserves of oil started to fall.

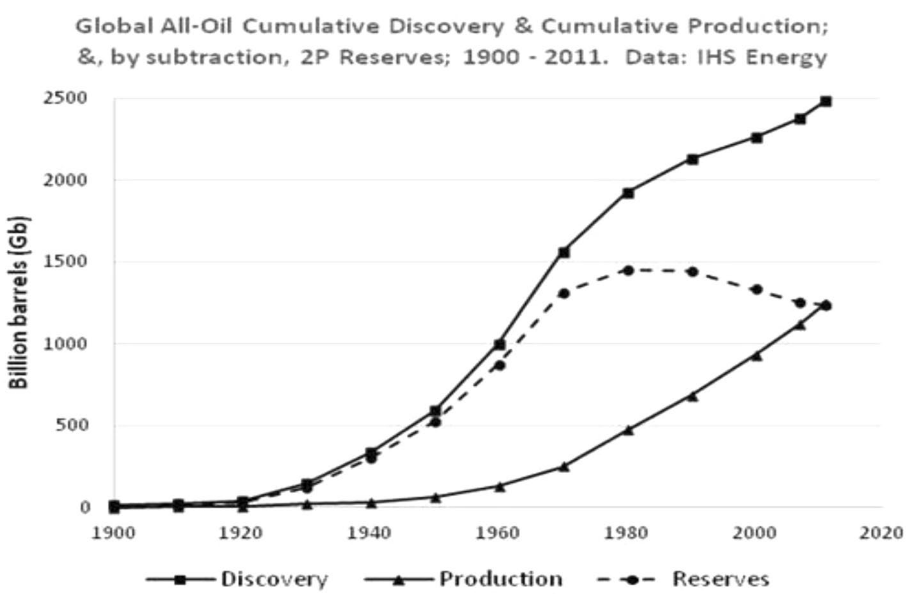

Fig. 1 Oil industry global cumulative backdated '2P' oil discovery data, Cumulative production, and hence 2P Reserves, 1900–2011. Source: IHS Energy 'Liquids' data; from Fig. 7 of Miller and Sorrell (2014) for cumulative discovery from 1900 to 2007, and from the corresponding Fig. 3 for cumulative production over the same period. Included in this plot are the data for end-2011 as given in the text of the Miller and Sorrell paper. Data are 2P, except for the US and Canada non-frontier areas, which are proved ('1P') data. The 2P data are backdated, in that they reflect information available to the IHS Energy as of 2007 (for the discovery curve), and to 2011 (for the final discovery data point). Reserves are calculated here (as done also by IHS Energy) by subtracting cumulative production from cumulative discovery. IHS Energy data are for oil in fields for conventional oil, and as announced in projects for non-conventional oils

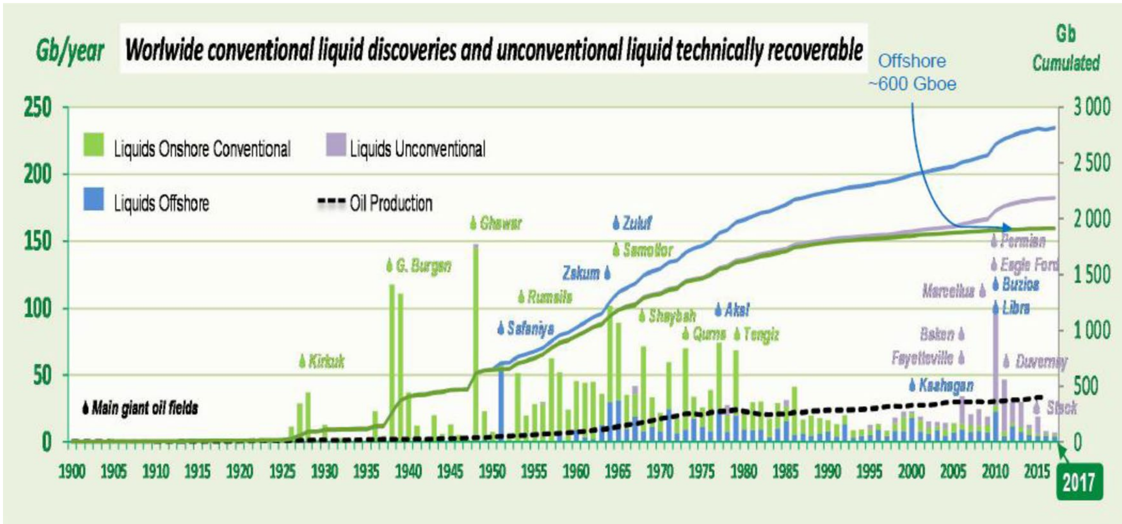

Fig. 2 Backdated annual and cumulative global oil discovery data, broken down into onshore and offshore conventional oil, and non-conventional oil, 1900–2017. Note: The text to this slide (translated from the French) says: Conventional oil discoveries less than annual production since the 1990s. Emergence of the unconventional (onshore) oil since 2005 compensates for the lack of [conventional oil] discoveries. Source: From a presentation by P.R. Bauquis and D. Babusiaux: '*L'offshore pétrolier et gazier situation actuelle et perspectives*, given at an ASPO-France meeting, 6 February 2019. The slide itself says: "*Source: IHS (Edin) for conventional discoveries volumes (@01/01/2018), BP (Statistical Review of World Energy) for production figures, & Rystad for unconventional figures.*"

Figure 2 shows similar backdated oil discovery data, here on both an annual and cumulative basis, and broken down into onshore and offshore conventional oil, and non-conventional oil, where the latter refers primarily to Canadian tar sands and US tight oil.

Figure 2 gives a clearer indication than Fig. 1 of the recent additions from US tight oil (but where it is incorrect to call these 'discoveries', as instead they report in the main the oil volumes projected for new tight oil projects added to the database at the dates shown). The conclusion from Figs. 1 and 2 is clear: most of the world's oil was discovered long in the past, and, despite the advent of US tight oil, much less in recent years. As a result, the global 'creaming curve' of cumulative oil discovery vs. date—certainly for conventional oil—has long since flattened towards the global URR asymptote.

This view is supported by recent data from Rystad, which records global annual 2P discovery of conventional oil as averaging only 6.2 Gb/year from 2013 to 2019 inclusive (Rystad Energy 2020). This is less than one-quarter of annual average production of conventional oil over these years, and hence represents a further drawing-down of global 2P reserves of this class of oil over the period by ~ 130 Gb.

Global Production of Conventional Oil

With these three ideas in place (the definition of conventional oil; that there is a lot of oil and other liquids still to access; and that global discovery of conventional oil has been in decline for over fifty years) we are now in a position to examine global production of conventional oil. This is shown in Fig. 3.

As Fig. 3 shows, global production of conventional oil has been on-plateau since 2005. This plateau came as a surprise to the majority of oil analysts, and raises two questions:

- Does the plateau reflect oil *resource limits*?
- Should it have been a surprise?

To answer these questions we examine URR estimates for global conventional oil and then apply the mid-point rule.

(a) Estimates of the Global URR for Conventional Oil

(i) Earlier URR Estimates Hubbert (1949) was one of the first to look at future global production of fossil fuels based on URR estimates, where for oil the global estimates then available, based on extrapolation of US oil discoveries by area of sediments to the world as a whole, suggested the global URR to be about 1000 Gb for onshore oil, and a further 1000 Gb for oil from continental shelves. Hubbert also provided URR estimates for oil from tar sands (200 Gb), and from kerogen (1000 Gb).

He then used a model of production 'peak-and-decline from about the URR mid-point', based in part on D. F. Hewett (1929), see Bentley (2016b, p69), to predict the global production of all fossil fuels combined; though—at least not in this 1949 paper itself—that for oil alone.

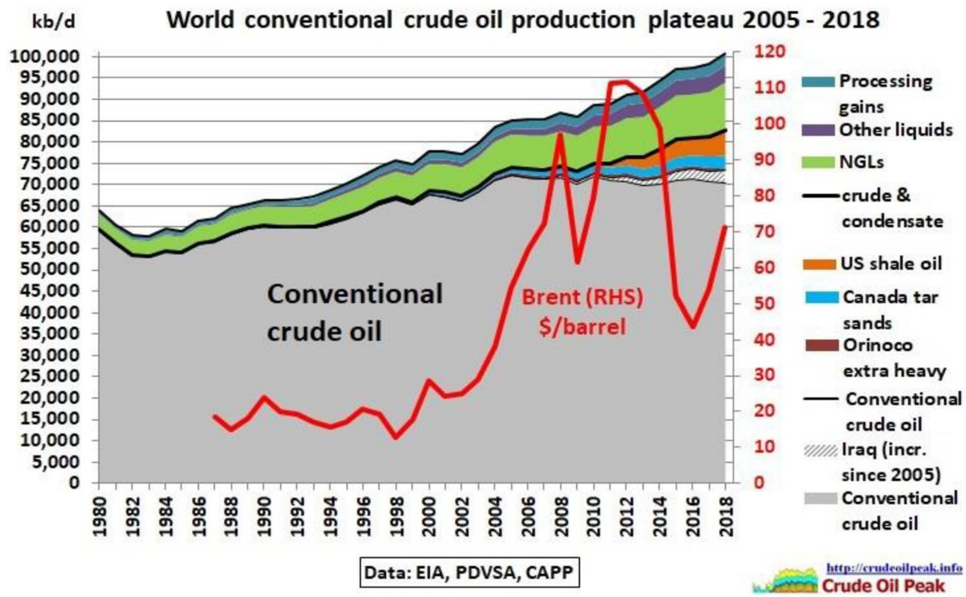

Fig. 3 Global production of 'all-liquids', by category of liquid, 1980–2018 (left-hand scale, kb/d) and Brent oil price (right-hand scale, $/bbl). Global production of conventional oil has been on-plateau since 2005 despite an on-average subsequent high oil price. This averaged > $80/bbl for most of 2007 to 2014, and > $100/bbl for a considerable part of this period. Notes: In recent years OPEC, and later 'OPEC + ', have had quotas in place; for recent data see: www.bloomberg.com/graphics/opec-production-targets. Note that Iran, Libya and Venezuela are exempt from these quotas, though all three have sanctions or other production problems to face. Note also that some major oil producers are close to, or past, their resource-limited oil production peak, so caution is needed as to whether some 'OPEC + ' country targets are achievable. Source: Chart by M. Mushalik. Data are from the US EIA for crude-plus-condensate, NGPLs, other liquids, and refinery gain; Canada tar sands data from the Canadian Association of Petroleum Producers; Orinoco oil data are from PDVSA. From time to time updates of this chart may be available at https://crudeoilpeak.info/latest-graphs

This 1949 estimate for the global conventional oil URR, at ~ 2000 Gb, was remarkably accurate given that Ghawar (the world's largest oil field) had only been discovered the year before and was still far from evaluated, and—more significantly—the peak in global discovery of conventional oil was not to occur until some 15 years later.

Hubbert subsequently published fairly regularly on the topics of both US and global future oil production based on URR estimates as these changed over time. Many organisations in the 1970s and early 1980s also gave URR estimates, and sometimes URR-based forecasts, including ESSO, Shell, BP, Mobil, Conoco, AGIP, Rand Corp., USGS, IFP, API, UK DTI, World Bank and a report for the UN (see, e.g. Bentley et al. 2007; Andrews and Udall 2015; and Bentley 2016a, p. 60). Most put the global URR for conventional oil in the range 1800–2500 Gb, and as result the majority of forecasts—on the basis of 'peak at mid-point'—forecast the peak in global conventional oil production as expected around the year 2000.

Subsequent URR-based oil forecasts included that of Campbell and Laherrère (1995, 1998). This used the Petroconsultants oil exploration and production (E&P) database to estimate the global URR for conventional oil as 1800 Gb; and using a 'peak at mid-point and exponential decline' model, concluded (1998) that: "*Barring a global recession, it seems most likely that world production of conventional oil will peak during the first decade of the twenty-first century.*"

Note that all the above forecasts were *explicitly* only for the production of conventional oil, and where the general view was that though very large potential resources of non-conventional oils were well known, these were seen as likely to only come into significant production once conventional oil was at or near maximum, and the oil price high in consequence.

(ii) More Recent URR Estimates Now we look at some more recent estimates for the URR of global oil, and where—especially since the advent of tight oil—one needs to be careful about what categories of oil are included.

The IEA's 2013 data in Fig. 4 indicate significantly higher estimates for the global URR of conventional than the earlier estimates given above; where the IEA here indicates ~ 3800 Gb for global conventional oil excluding EOR, and ~ 4200 Gb if EOR is included.

But Campbell, Laherrère and others point out that these IEA estimates are based on USGS assessments of undiscovered oil, which since the year 2000 have assumed large amounts of 'reserves growth' not only for the US but for other countries also. As explained in Bentley (2016a, Section

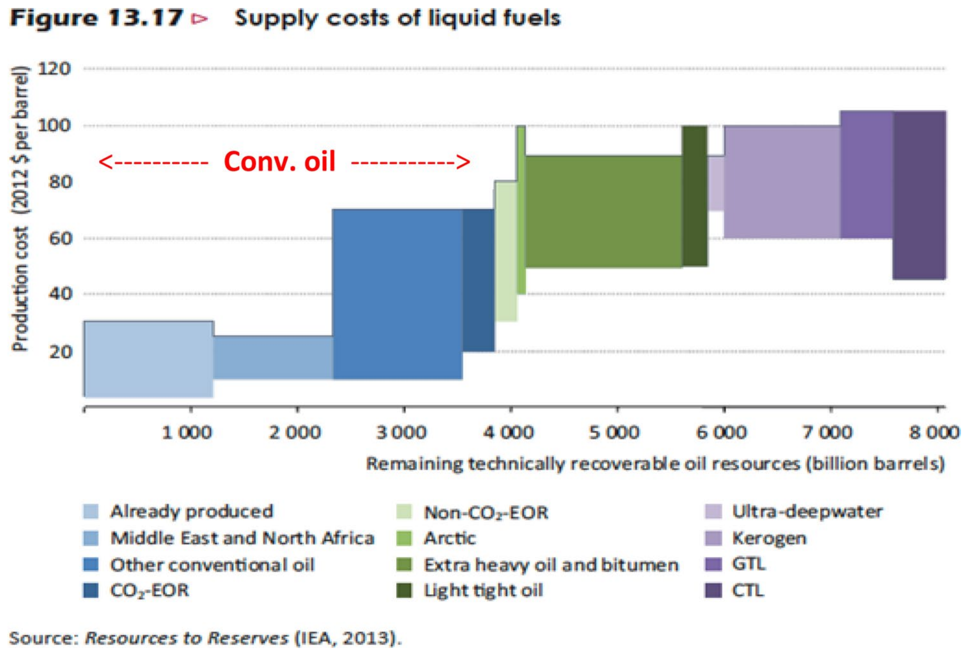

Fig. 4 Estimated Global already-produced, and Remaining technically recoverable volumes of oil by category (Gb) vs. Production cost range ($2012/bbl). Notes: EOR: Enhanced oil recovery; CO2-EOR: EOR using CO_2; Kerogen: Oil produced by heating rock containing the oil precursor kerogen; GTL: Gas to liquids; CTL: Coal to liquids. Not shown are NGLs (which are produced from gas), biofuels, synthetic fuels and refinery gain. Source: IEA, '*Resources to Reserves*' report, 2013

A4.3), there is considerable doubt over these reserves growth factors. Moreover, both Campbell and Laherrère point out problems of potential overstatement in the 2P oil discovery data themselves as held in oil industry datasets, particularly for Middle East and former Soviet Union countries, and as a result suggest global URRs for conventional oil, and excluding NGLs, as more likely to be over 1000 Gb less than the IEA's 2013 estimates, at around 2200 Gb (Campbell), and 2600–3000 Gb (Laherrère).

This view of the IEA's 2013 estimate of the global conventional oil URR as probably high is supported by the IHS Energy 2011 data shown in Fig. 1. Here if it is assumed that oil discovery to the year 2000 was primarily of conventional oil then a 'discovery trend' URR asymptote for this class of oil of ~ 2500 Gb seems reasonable. And likewise,

Table 1 Estimates of the Global oil URR by category (Gb)

	'Reg Conv.'	Conventional oil[e]	All-oil + NGLs
Range of estimates 1949 to 1981[a]		1800–2500	
Campbell and Laherrère 1998		1800	
'Low' range of estimates 1992 to 2005[b]		1800–2836	2670–3000
'High' range of estimates 1998 to 2005[c]		3303	4000–4500
Campbell, data as of 2010; Table 2	2000	~ 2200	
IEA 2013[d]		3800–4200	
Extrapolation from Fig. 1 (IHS 2011)		2500	
Extrapln. Figure 2 (IHS and Rystad 2017)		2700	
Globalshift 2018 prod. to 2100; Table 2			3250
Rystad Energy 2018; Table 2			3670
Laherrère, current		~ 2600–3000	

Conv.: Conventional oil; generally taken as crude oil excluding light-tight oil, tar sands and Orinoco oil, and oil produced from kerogen. All-oil: All crude oil. 'Reg. Conv.': Defined by Campbell as conventional oil less deep-offshore and Arctic oil. NGLs: Natural gas liquids

[a]Data from Table 1 of Bentley (2015a); and where the URR estimates used by Hubbert for global conventional oil less NGLs were: in 1949: 2000 Gb; in 1956: 1250 Gb; in 1969: in the range 1350–2100 Gb

[b]Data from Table 2 of Bentley (2015a), and excludes a 'what-if' outlier of 3000 Gb.

[c]Data from Table 3 of Bentley (2015a). 3303 Gb is an EIA estimate, and includes NGLs

[d]Data from Figure 4, giving the URR range for conventional oil without, and with, EOR

[e]Early URR estimates for conventional oil exclude NGLs, later estimates may include some or all of NGLs

if the IHS and Rystad data to 2017 of Fig. 2 are used to indicate 'discovery-trend' URRs, then these data indicate a global URR for conventional onshore oil of about 2000 Gb, with conventional offshore oil adding perhaps 700 Gb once future discoveries are in, for a global conventional oil URR of ~ 2700 Gb.

Finally we can look at three additional recent URR estimates given in Table 2 in Annex 1. Campbell's global URR estimate in 2010 for 'Regular Conventional' oil is 2000 Gb, with 55% of this having been produced by that date. Globalshift Ltd.'s end-2017 estimate of cumulative production of all-oil plus NGLs to 2100 (and hence inferred URR) is 3250 Gb, with 45% of this having been produced by that date. And Rystad's 2017 URR estimate for all-oil including some NGLs is 3670 Gb, with 40% of this having been produced by that date.

These estimates, plus additional URR data, are summarised in Table 1.

As Table 1 shows, and contrary to the general perception, URR estimates for *global conventional* oil have been remarkably consistent over the seventy years or so since they were first produced. If we place greater reliance on URRs based on extrapolation of the discovery trend (Figs. 1 and 2) than on higher URR estimates often based on USGS estimates which include significant quantities of oil in 'reserves growth', then URR estimates for global conventional oil have grown from 1800–2500 Gb several decades ago to perhaps 2200–2800 Gb today. If the mid-point rule is used, this represents a shift in the expected date of the peak of conventional oil over this period of less than 10 years.

(iii) Impact of Oil Price on URR However, in looking at URR estimates we need to recognise that if the oil price goes significantly higher then additional conventional oil will likely be forthcoming, generated by a combination of additional exploration, in-fill drilling in existing fields, access to small and difficult finds currently considered too expensive to produce, and from the further application of EOR.

For an illustration of the anticipated impact of oil price on production, see the significant changes in future all-liquids supply forecast by Rystad Energy's 2015 model in response to assumed oil price levels of $50, $100 and $120/bbl, as shown in Fig. 6 of Wold (2015). And more recently, we understand that Rystad's current UCube model suggests that an oil price of $120/bbl combined with sustained levels of record Capex spending could push the global production of conventional oil plus NGLs to a peak of around 113 Mb/d by the year 2060.

But in this context it is important to note that $120/bbl is an oil price the global economy does not like, and so one should perhaps thus not expect too much in the way of increases in the future production of conventional oil from increases in oil price.

(b) Conclusions on the Global Conventional Oil Plateau

We are now in a position to decide if the current plateau in global production of conventional oil is resource-limited. As indicated above, if current 'discovery trend' estimates for the URR of this class of oil are used then the URR range is perhaps ~ 2200–2800 Gb. Given that ~ 1400 Gb of conventional oil has been produced to end-2019, then the 'peak at mid-point' rule indicates that the global conventional oil plateau since 2005 shown in Fig. 3 does indeed reflect resource limits, at least at oil prices up to well in excess of $100/bbl. We note, however, that the high oil price driven by these resource limits has enabled global production of conventional oil to stay on-plateau for over a decade, rather than see the early decline that some analysts envisaged.

And this answers the second question posed above. The many forecasts over the years that combined the mid-point rule with URR estimates for global conventional oil had nearly all suggested a maximum in the production of this class of oil around the year 2000. The 2005 plateau should not have come as a surprise.

Consequences of the Plateau in Global Conventional Oil Production

Now we turn to some of the consequences of the world reaching its resource-limited conventional oil plateau in 2005. These have included a significant rise in the price of oil, this being a contributory factor to the 2008/9 global recession, high current levels of global debt, a fall in the average EROI ratio of oil production, increased CO_2 emissions from oil, and the rise in tight oil production in the US, with impacts on the US economy and wider geopolitics. These consequences are discussed below:

Rise in the Price of Oil

Figure 5 plots global oil production and real-terms oil price since 1965.

As Fig. 5 shows, there have been dramatic changes in the annual average real-terms price of oil since 1965, varying from low to high by a factor of 12, a much larger price range than most mainstream commodities experience. The reasons for the earlier price changes are covered briefly below, but since 2004 the oil price increase has largely reflected the fact that since that date the world's additional ('marginal') barrels of oil to meet demand have had to come from increased production of non-conventional oils and 'other liquids', and where, as Fig. 4 indicates, these are generally significantly more expensive to produce than conventional oil.

Here we discuss two aspects of this post-2004 oil price rise: a closer look at the factors driving this increase, and a caveat on oil production cost data. (Later in this paper we set this price increase in an historical perspective and draw conclusions on the primary drivers of oil price.)

(a) A Closer Look at Causes for the Oil Price Rise After 2004

Although the oil price rise after 2004 was driven fundamentally by the world approaching its resource-limited plateau in conventional oil production, it is useful also to look at two specific triggers behind this price rise.

Figure 6 shows the changes since 1994 in *total* crude oil production (not just of conventional oil) by country as given by EIA data. As the lower black line indicates, a wide range of oil-producing countries saw their combined production of total crude oil as roughly on-plateau from 1998 to 2004, and then decline from 2005. As a result, despite production increases from the other countries shown, global total crude was itself on plateau from 2005 to 2010, helping to trigger the 2004 to the 2008 price spike, and also the high prices from 2010 to 2014. Furthermore, as shown, with the exception of increases from Iraq (conventional oil), and the US (tight oil), production of global total crude has remained on-plateau since 2005.

Also relevant to the oil price rise since 2004 were the oil exports that were available. These are shown in Fig. 7 for the period 1980–2016.

As can be seen, global oil exports peaked around 2004, and reached the same level in 2016. One of the drivers for the 2004 export peak were production declines in oil exporters Norway, UK, Venezuela, Mexico and Iran reflecting *resource limits* in these countries; another driver was lack of compensating additional output from Russia and OPEC, in part reflecting *production constraints* in these regions (see relevant posts at https://crudeoilpeak.info).

(b) Caveat on Oil Production Cost

Secondly in this section on oil price we offer a caveat on oil production costs. The estimates of the production costs of the various classes of oil and other liquids as of 2013, as shown in Fig. 4 and for example in Aguilera (2014), do not look so very high given some of the oil prices since 2004. But two points need to be made:

- Firstly, oil prices of ~ $100/bbl and above in real-terms have generally triggered global economic slowdowns or even recessions as discussed below.
- Secondly, a higher oil price generally leads to a higher cost for oil production. This comes about in two ways: Usually recognised is the fact that higher oil prices tighten rig rates etc., as well as—over a slightly longer timeframe – increases in wage costs of people with oil production skills.

But a more fundamental effect, often overlooked, is the manner by which the cost of oil feeds into the costs of oil production, doing so in part directly via the oil used in the production processes, but more importantly indirectly by raising the cost of nearly all goods and services across society. One of us (R. Bentley) saw this 'cost-push' mechanism at work when employed by a Canadian oil company following the oil price shocks of the 1970s. The company's house magazine over quite a number of years said in effect: 'Do not worry too much about the high price of oil since

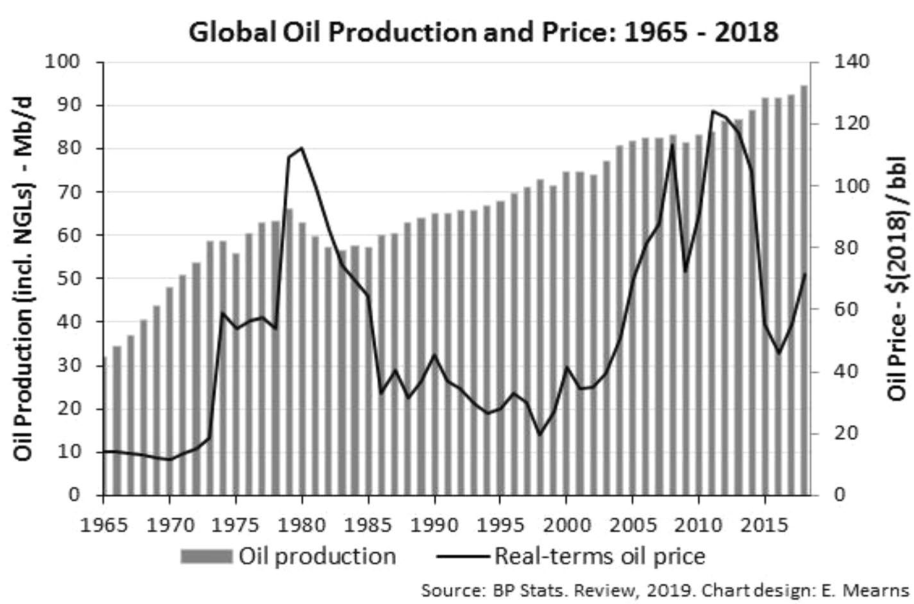

Fig. 5 Global Oil production, and Real-terms oil price, 1965–2018. Note: Oil prices (right-hand scale) are *BP Stats Rev*. data of annual average real-terms ($2018) oil prices, calculated by deflating money-of-the-day oil price by the US CPI. Not shown: Real-terms ($2018) oil prices from 1923 to 1964 ranged from $11/bbl to $27/bbl, and averaged $18/bbl over the period

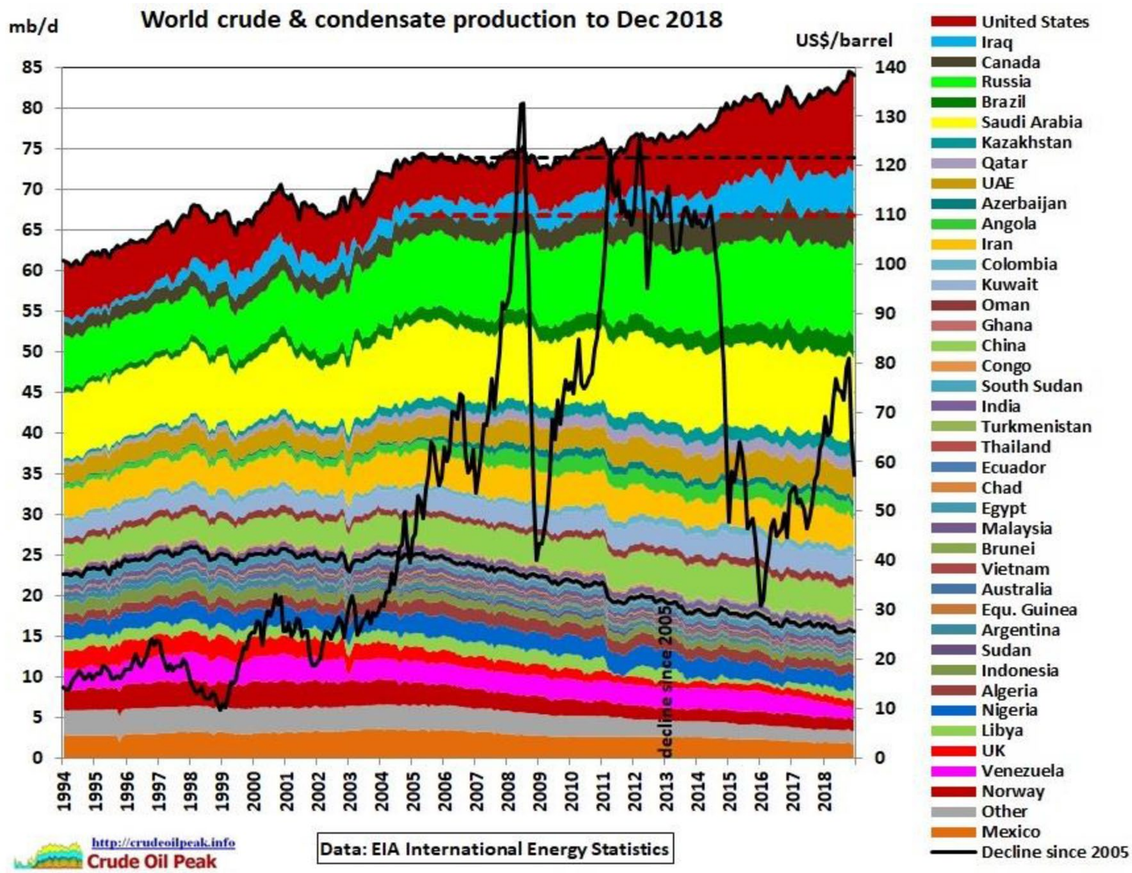

Fig. 6 Global crude oil production by country, and oil price, 1994 – Dec. 2018. Notes: Data are for 'crude plus condensate'. In understanding these oil production data, consideration is needed of OPEC (and later, OPEC+) quotas; and also export sanctions on Iran. Oil price shown is monthly-average, in money of the day. Source: Chart produced by Matt Mushalik, data from EIA

tar sands oil can be produced at not much higher cost'; but where, as time passed, this 'not much higher' cost itself kept rising, and always stayed just a bit above the then-current price of oil.

And the above, in turn, almost certainly reflects a key lack of economic knowledge that as far as we understand still awaits full resolution. It is often said that since the cost of oil to an economy is only a small percentage of its GDP, then the impact of a rise in the price of oil on the economy must be similarly small. The many economic slowdowns and recessions linked to increases in the price of oil (see below) strongly suggest that a wider understanding of the impact of the price of oil—and of energy more generally—on economic activity is needed; see e.g. Ayres and Warr (2009) or Keen et al. (2019).

The 2008/2009 Global Recession

A second consequence of the world reaching its resource-limited plateau of conventional oil in 2005 was as a contributory cause of the global recession of 2008/9, where this was triggered in part by the post-2004 price rise.

It has long been known that recessions are often associated with rapid increases in the oil price, Fig. 8.

Given the apparent linkage shown in the figure, it should not have been a surprise that a significant period of global recession followed the steep ramp-up in oil price from 2004.

The global recession of 2008/9 was triggered first in the US, where the high price of oil impacted consumer spending, vehicle sales, and house prices (the later in part reflecting the inability to repay mortgages due to the rising cost of commuting), see Hamilton (2009a). Hamilton noted that: "Oil prices thus appear to have exerted a moderate drag on [US] real GDP in 2005–06 and made a more significant negative contribution in 2007–08. … This episode should thus be added to the list of U.S. recessions to which oil prices appear to have made a material contribution." The US recession was followed by the wider global 2008/9 recession, in part resulting from collapse of global liquidity from the failure of collateralized debt obligations, credit default swaps and similar instruments.

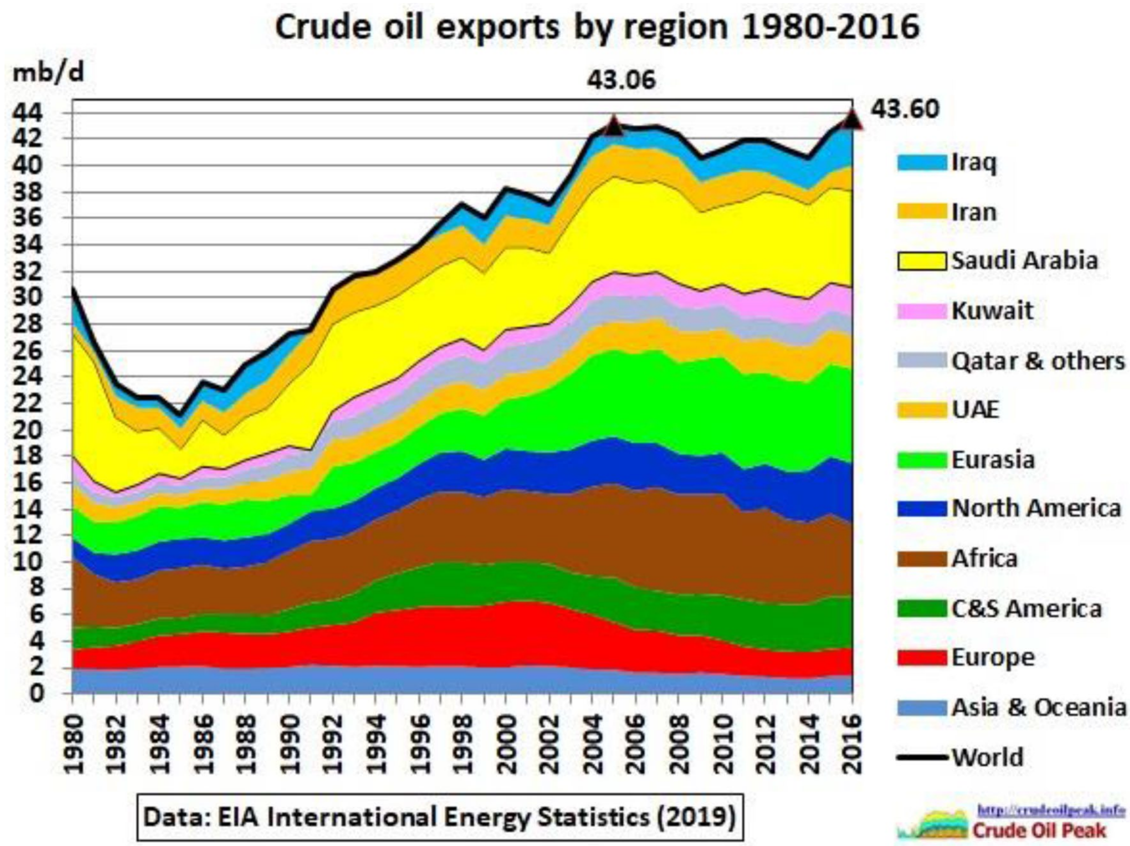

Fig. 7 Crude Oil Exports by Region, 1980–2016. Note: In examining these oil exports, consideration is needed of OPEC (and later, OPEC+) quotas, and also the recent export sanctions on Iran. Source: Matt Mushalik

Global Levels of Debt

The world's debt reached a then all-time high at ~ $250 trillion, some three times global GDP, in the third quarter of 2019 (IIF 2020). This debt built up prior to the 2008 recession from rapid expansion of easy borrowing, during the recession from government rescue of banks and other companies, and since the recession from quantitative easing in attempts to finance economies out of recession. A number of economists point to this debt as a sword of Damocles waiting to fall, with the recent global increases in debt from the 2020 virus pandemic thinning the hair on which it hangs.

Fall in Average Oil EROI Ratio

A fourth outcome of the plateau in global conventional oil relates to energy return on energy invested (EROI). This ratio is an often overlooked but critical indicator of prospects for energy supply. As Fig. 3 shows, the marginal barrels required to meet global liquids demand since 2005 include a range liquids types, and where most of these have lower EROI ratios than conventional oil (Murphy 2014). EROI can also be expressed in terms of the net-energy ratio (NER). This gives the net energy that a barrel of oil or other liquids contributes to the global energy system after the energy required for its production is subtracted off, and is calculated as: (Energy out – Energy in)/Energy out, which is the same as: (EROI – 1)/EROI.

The NER for each category of liquid can then be multiplied by the production volumes of these liquids (as in Fig. 3) to calculate the total net energy delivered to society by these liquids. Though the IEA for the first time included data on the average EROI of oil production over time in its 2018 *World Energy Outlook*, to our knowledge the only detailed oil forecasts that have carried out net-energy calculations to-date are those of Campbell (2015) and Solé et al. (2018).

Note that EROI imposes two very different kinds of limit as explained for example in Carbajales-Dale (2019). In a *steady-state* situation EROI is a useful measure, but for a *dynamic* situation when an energy type is growing (or diminishing)—for example when an energy system is transitioning from one energy type to another—the PROI

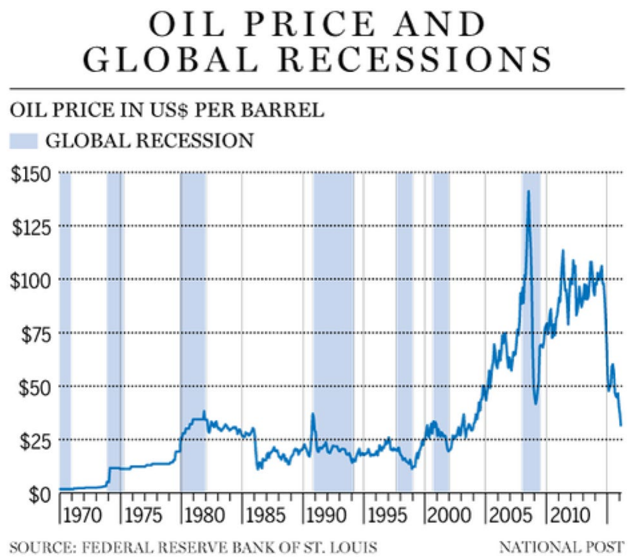

Fig. 8 Apparent linkage between oil price increases and onset of global recessions. Note: Oil price is shown in money of the day; unlike Fig. 5 where the price is in real terms. Source: Martin Pelletier, Financial Post Feb. 29, 2016, article titled: '*Is the oil price plunge a recession trigger? History says otherwise*'. Pelletier writes: 'History has proven that every time there was a major global recession it was immediately preceded by a large spike in oil prices followed by a large drop during the recession'

(power out divided by power in) ratio needs to be used instead. An exemplar of the latter is photovoltaic (PV) systems, where up to 2018 the rapid growth of these systems, combined with their up-front energy requirement and moderate EROI, has meant that to-date the world's PV systems have yielded surprisingly little net energy to society. As far as we know there are very few models that examine this important topic of the impact of PROI ratios on the current global energy transition, one of these being King and van den Bergh (2018).

Before we leave this topic, it is important to note that there are still many unresolved issues concerning the proper application of EROI, see the discussion and references in Jefferson (2019).

Increased GHG Emissions from Oil Production

Also related to greater energy inputs, many of the marginal barrels required to meet global 'all-liquids' demand since 2005 have higher per barrel greenhouse gas (GHG) emissions than conventional oil. Note that the GHG emissions referred to are usually those during the production, refining and transport of these liquids, and must include both the indirect as well as direct emissions; the relatively large emissions from combustion of these liquids are generally similar to conventional oil. Modelling of future global GHG emissions needs to take these differences by fuel type into account, see Nduagu and Gates (2015), and Masnadi et al. (2018).

Rise of Tight Oil Production

The final outcome from the plateau in global conventional oil production that we consider here is the rise of tight oil, primarily in the US though also elsewhere. Though oil has long been produced by horizontal drilling and also by hydraulic fracturing, the rapid rise of US tight oil production was driven by the sustained high oil price explained above, combined with an innovative combination of horizontal drilling, newer fracking fluids and extensive use of proppants. Other factors included US land-ownership rules, relatively light regulation and the availability of credit (the latter itself a reflection of the high oil price and low interest rates).[1]

This rapid rise of US tight oil, unexpected by nearly all oil analysts, has had a wide range of impacts. These include:

- Reduction in the cost of US oil imports, falling from up to perhaps $450 billion per year in 2008 (about 2/3rds of the country's defence budget), and representing a per capita cost of perhaps $1500/year, to near zero today.
- Engendering the view by many oil analysts that the world now faces 'oil abundance', see Annex 2.
- The US being perhaps less concerned about Middle East political developments, though still recognising the potential impact of oil supply disruptions on allies.
- Wider geopolitics: In February 2020 for example, after Russia had temporarily cut oil exports to Belarus, the US Secretary of State told Belarus that the US was ready to provide all of that country's oil needs (*Financial Times* 2020).

Note that these economic and geopolitical changes from tight oil may be fairly short-lived: a number of sources including Wang et al. (2019), Hughes (2019) and *World Oil* (2019) warned of possible constraints to US tight oil production even before the recent virus-induced oil price collapse.

[1] In the context of tight oil we note that George P. Mitchell, the pioneer of shale gas (which in turn led to tight oil), was "in the 1970s a sponsor of the work of Dennis Meadows, whose Club of Rome study 'The Limits to Growth' was a global wake-up call on the pressing need for sustainable energy technologies and food sources worldwide. … The Mitchells also underwrote the National Academies' 'Our Common Journey: A Transition Toward Sustainability." [Wikipedia, accessed 8 Nov. 2019.]

Overall, we judge that the consequences listed above of the world reaching its resource-limited plateau of conventional oil production have been significant, and need to be better recognised.

Discussion: Oil Prices in an Historical Perspective

In this section we discuss the significance of the oil price increase since 2004 by placing it in its historical context, and using this to draw conclusions about the main drivers of oil price. First we give a brief review of the literature on the subject.

Brief Literature Review

The literature on the price of oil has been extensive, and includes among many other studies those by Fattouh (2007), Hamilton (2009a, 2009b, 2011), Benes et al. (2012), the World Bank (2015, 2019), Baumeister and Kilian (2016) and Kaufmann and Connelly (2020). The explanations given for changes in the oil price seem almost as numerous as the studies; for example:

– Fattouh writes: "*Some observers argue that the oil market has undergone structural transformations that have placed oil prices on a new high path. … Others interpret the recent oil price behaviour in terms of cyclicality of commodity prices.*"
– Baumeister and Kilian found: "*… most major oil price fluctuations dating back to 1973 are largely explained by shifts in the demand for crude oil.*"
– The World Bank (2015) saw the change in oil price as in part reflecting a "*supercycle that began in the early 2000s.*"
– While Kaufmann and Connelly, examining oil prices between 1938 and 2018, found the price drivers to be "*a combination of speculative bubbles … and … market fundamentals.*"

The methodologies used in such studies have also been many, and have included correlations with a range of economic indicators; examination of potential future oil supply as indicated (unfortunately misleadingly, see the discussion of reserves in the Methodology section earlier) by the evolution of *proved* ('1P') reserves; use of estimates of the total recoverable oil remaining (but where this also misleads by ignoring mid-point peaking); and analysis of external factors such as imputed OPEC behaviour, etc. Of the papers listed above we judge those by Hamilton, and that of Benes et al. (2012) which combined oil industry 2P oil discovery data with economics, to give the best explanations.

However, what has been lacking in our view in nearly all the literature on oil price (Benes et al. excepted) has been a proper understanding of the supply side as indicated by the oil industry 2P oil discovery data. In part this has been due to the difficulty analysts have had in accessing these data, and in other cases by analysts not being aware that such data were needed.

Oil Price Historical Perspective: 1923–2020

So here we attempt to set the oil price increase since 2004 into what we see as its correct historical context. We do this by drawing on the findings set out in Bentley and Bentley (2015a, b), and where these in turn relied significantly on two sources: the outstanding history of oil by Yergin (1990), and the backdated 2P oil discovery data—the crucial information of how much conventional oil was discovered, and when—given in the IHS Energy (earlier, Petroconsultants) 'PEPS' by-country oil and gas exploration and production database.

For this analysis we divide the near-century from 1923 to early 2020 into six periods, and examine the major factors determining the oil price in each of these periods. (Prices are averages over the periods of annual real-terms ($2018) oil prices from *BP Stats. Rev*., 2019.)

Overall, we find that except for two periods of very high oil price resulting primarily from oil supply constraints (1974–1982, and 2004–2014), and of very low price from the fall in demand in 2020, the real-terms oil price has climbed in three successive steps, averaging respectively $17, $35 and ~ $60/bbl, reflecting the increasing marginal cost of oil over this period as production has become progressively more difficult.

We start this explanation with the half-century from 1923 to 1973.

1923–1973: Average Annual Real-Terms Oil Price: ~ $17/bbl

As Figs. 1 and 2 show, between 1923 and 1973 the world saw a large excess of oil discovery over consumption. (For an explanation of why, contrary to mainstream economic theory, oil companies continued to look for new oil when a large oversupply existed see Bentley and Bentley 2015a, Sect. 5.2.) This long period of oversupply, combined with downward pressures on oil price from access to giant fields in the Middle East and elsewhere, increased scale of production, and gains from technology in exploration, production and transport of oil, resulted in the oil price staying low, averaging just ~ $17/bbl. Indeed, over this period a range of company agreements and prorationing in the US had been introduced to stop the oil price from falling so low as to further damage oil producer margins and oil owner royalties.

1974–1982: Oil Shocks: Average Oil Price: ~ $55/bbl, and ~ $100/bbl

This period of low oil price came to an end with the first and second oil shocks in the 1970s. The first shock, triggered by the Yom Kippur war, lasted from 1974–1978 and resulted in an average oil price of ~ $55/bbl. The second shock, triggered by revolution in Iran and then reflecting the Iran–Iraq war, lasted from 1979–1982, with the oil price averaging ~ 100/bbl.

It is not adequately recognised even today that a key factor in these oil shocks was the US reaching its peak of conventional oil production in 1970. OPEC, founded in 1960, had long argued that it should receive a higher price for its oil. It tried several times before 1973 to achieve this by cutting back on production, consciously copying the prorationing of the Texas Railroad Commission. But on each occasion the US opened its prorationing taps and the attempt failed, see Yergin (1990). It was only with the US past its peak in conventional oil production, and hence with prorationing at an end and its oil taps fully open, that OPEC production restrictions—albeit triggered by politics—could raise the price of oil.

The fact that relatively small reductions in oil volume to the market could make for such large increases in oil price mainly reflects the short-term price inelasticity of oil, but probably coupled with unfounded fears at the time of oil 'running out'—see Bentley (2016a, pp 179–182).

1986–2004: Average oil price ~ $35/bbl

Subsequently oil came on-stream from a range of new oil provinces, but all discovered *before* the 1970s oil price shocks. In the face of this new oil, OPEC could not sustain the ever-deeper production cuts required to keep the oil price high, particularly Saudi Arabia which bore the brunt of these cuts.

These new oil provinces included Alaska, the North Sea, in Mexico, and far within Russia, all of which had been discovered before the 1970s oil shocks but where much of this new oil was intrinsically more expensive to produce, and so had seen little exploitation earlier. As a result of these higher cost marginal barrels, after three years of price transition (1983–1985), the real-terms oil price over the following nearly two decades (1986–2004) averaged ~ $35/bbl.

2005–2014: Average Oil Price ~ $100/bbl

Then the world again faced roughly a decade of very high oil prices, of the order of 100/bbl, a real-terms price not seen since the second oil shock of 1979.

Partly this price reflected increased production of even more expensive conventional oils, such as deep offshore and EOR oil, but as explained above was primarily a result of the world reaching its resource-limited plateau in conventional oil in 2005, such that the marginal barrels had to come from the often far more expensive non-conventional oils which initially—before the significant ramp-up of US tight oil—included tar sands and coal-to-oil, having production costs up to $90/bbl and above (Fig. 4).

Note that as Fig. 5 shows, though the oil price over this period was high on average, it fell significantly in 2008 primarily due to reduced demand caused by the 2008 global recession, but where the wide spot price range (from a Brent high of $146/bbl to a low of $38/bbl) was probably exacerbated on the upside by Chinese stock-building ahead of the Olympic Games, and in both price directions by speculation.

2015—2019: Average Oil Price ~ $60/bbl

Over the recent four years from 2015 to 2019, the rapid rise in the production of US tight oil, and fall in production cost of this oil due to both scale and advancements in technology, tied the oil price back to an average of ~ $60/bbl; reflecting approximately the average marginal cost of this oil in providing—together with NGLs—the bulk of the marginal barrels.

Note however that over this period also, OPEC, and more recently 'OPEC + ', adjusted quotas with the aim in part of recouping the often higher 'fiscal price' of oil of some of the cartel's members, where this is the price needed to cover government expenditures (currently for example said to be $40/bbl for Russia, $80/bbl for Saudi Arabia, and higher still for some other producers).

First Part of 2020: Oil Price Down to ~ $25/bbl.

And most recently of all, a fall in the Brent spot price (at the time of writing) to ~ $25/bbl, where this reflects three factors:

- Supply/demand: The oil price falling as demand falls due to the virus.
- Oil's well-known short-run price inelasticity, high compared to many other commodities.
- 'Politics': The initial falling-out within OPEC + with Rosneft long being unhappy that production cuts were supporting US shale oil producers, and later the reconciliation within OPEC + plus promised restraints from other suppliers.

It is currently an open question as to whether these agreements, combined with high-cost producers (such as US shale) reducing production or going out of business, will be enough to bring the market back to the 'marginal barrels' price, or even to producers' 'fiscal' prices. (See also Annex 2 on views and forecasts of future oil supply.)

Summary: Oil Prices 1923–2020

From a nearly a century of oil prices we conclude that price is set primarily by the basics of the *supply/demand balance* and by the *marginal cost of oil*, as follows:

- When there is potential significant oversupply of oil, either due to excess discovery (as in the period 1923–1973) or to a rapid fall in demand (as in 2020), the oil price can go very low, and measures are needed to stop it from going too low.
- When supply is tight, as from 1974 to 1982 due to the resource-limited peak of US conventional oil production combined with OPEC aspirations and politics, or from 2005 to 2014 due to the resource-limited plateau in global conventional oil production, the price goes high. It can go very high for short periods, but is then limited over longer periods by demand-destruction (post-1973 and 1978, and briefly post-2008), and by new—but often significantly more expensive—sources of oil coming on-stream.
- When supply and demand are roughly in balance, even if this is achieved by agreements between the major producers, prorationing, or OPEC quotas for conventional oil, or by changing the rate of drilling and well completions for tight oil, the price of oil is set essentially by the cost of the marginal barrels, with this increasing over time as production has become increasingly difficult.

Note that over this near-century there has been a range of 'non-technical' factors (those not directly related to the exploration, production, transport or refining of oil) that have also fed into the supply/demand balance. These include:

- 'Production aggression' of oil independents (mainly in the US from the latter part of the nineteenth century until prorationing, and again the shale oil independents in the 2010s) who in out-competing with each other can send the oil price spiralling to financial damage for all.
- Cartels; including originally Rockefeller's, later the 'Seven sisters', then OPEC, and most recently, OPEC+; and where these initially sought good returns if producers, and adequate rent if owners, but where more recently the goal has become cartel members' 'fiscal prices'.
- Oher forms of market control, including US prorationing, and by fiat in many nations during wartime.
- 'Politics', such the Yom Kippur war, Iranian revolution, and civil wars in Syria or Algeria.
- Speculation.
- And finally the demand for oil, itself is partly a function of oil use in the past in providing the funds for innovation and investment needed to support increasing demand for oil.

Conclusions

This paper's conclusions are as follows:

1. To understand global oil supply it is important to differentiate supply by type of oil; to not be misled by proved ('1P') oil reserves; and to recognise that conventional oil production in a region typically reaches its resource-limited peak when roughly half of the region's ultimately recoverable resource (URR) of this oil has been produced.
2. URR estimates of conventional oil indicate that global production of this oil reached its resource-limited plateau in 2005, certainly at oil prices up to well above $100/bbl.
3. The approximate date of this resource limit had been predicted correctly for many years.
4. The plateau in conventional oil production has had serious consequences, with impacts not only for oil and energy supply, but also for transportation, economic growth, climate change and politics. These consequences include a significant rise in the price of oil, this in turn being a causal factor of the 2008/9 global recession, high levels of global debt, a fall in the average EROI ratio of oil, increased GHG emissions from oil production, and the rise of tight oil production in the US with impacts on the US economy and wider geopolitics.
5. The rise in the oil price caused by the plateau of conventional oil can be set in an historical context, and conclusions drawn on the main drivers of oil price. Overall we find that except for two periods of very high oil price resulting primarily from oil supply constraints (1974–1982, and 2004–2014), and of very low price from the fall in demand in 2020, the real-terms oil price has climbed in three successive steps, averaging respectively $17, $35 and ~ $60/bbl, reflecting the increasing marginal cost of oil over this period as production has become progressively more difficult.
6. Resource limits indicate that global production of conventional oil will decline soon unless the oil price rises significantly.
7. As Annex 2 shows, currently there is a wide range of views on future oil production. These include global all-liquids supply already seeing resource-limited constraints; such constraints being a myth; and oil produc-

tion falling soon because of demand reduction. Given the importance of the topic there is a need to improve global oil forecasting, including access to oil industry 2P data, examination of the need to adjust downward 2P oil discovery data in some Middle East and FSU countries, inclusion of EROI data into models, and examination of 'peak demand' modelling.

8. Finally we note that the world would seem to be facing a difficult situation on oil supply. As currently configured, the global economy requires oil supply to increase significantly to meet the economic needs and expectations of its growing population. But supply of low-cost oil is in decline, and the world must use less oil if climate change goals are to be met. Resolving this conundrum may require global cooperation, good decision-making, and informed understanding from the world's inhabitants.

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Compliance with Ethical Standards

Conflict of interest All authors contributed to this study, and have read and approved the final manuscript. On behalf of all authors, the corresponding author states that there is no conflict of interest.

Annex 1: Data—Definitions, Reliability, Sources and Calculation Methods

Categories of Oil

There is no agreed classification of types of oil, but the following is used fairly generally, albeit often with significant modification:

- Conventional oil: Light or medium density oil occurring in discrete oil fields, usually having an oil–water contact, produced by primary (own pressure, or pumping) or secondary (natural gas or water injection) recovery techniques. Currently this class of oil supplies about 70% of global 'all-liquids', and has constituted the vast majority of oil produced to-date.
- Enhanced oil recovery (EOR): Covers a wide range of techniques to enhance oil production from a reservoir, sometimes classed as tertiary recovery, and includes thermal stimulation, CO_2 or nitrogen injection, and injection of a range of other chemicals to improve recovery. EOR may increasingly include the use in conventional oil fields of techniques developed for recovery of tight oil.
- Non-conventional oil: Typically refers to oils from extensive accumulations, and includes: light-tight ('shale') oil produced by horizontal drilling combined with hydraulic fracturing and use of proppants; heavy oils produced by thermal means; and oil from tar sands and the Orinoco basin. We distinguish these oils from conventional oil as their production is typically more complex (and hence usually more costly) than for conventional oil because either the oil itself, or the material in which it is located, needs physical alteration for the oil to be produced.
- Natural gas liquids (NGLs): Liquids produced from gas reservoirs, either on production, or after treatment of the gas by a processing plant (where the latter are classed as natural gas plant liquids, NGPLs).
- 'Other liquids', which include:
  - Oil produced from kerogen ('oil shale' oil), coal (coal-to-liquids, CTLs) or gas (gas-to-liquids, GTLs).
  - Oil produced from biomass, either directly or via chemical conversion.
  - Synthetic oil, produced chemically from non-oil feedstocks.
  - As with the non-conventional oils these 'other liquids' are usually more expensive to produce than conventional oil, and moreover often have investment/production profiles more akin to mining than conventional oil production.
- Refinery gain: The increase in volume (but not energy) resulting from the processing of oil to produce lighter fractions.

Because the available oil data often do not break down into this level of detail, in this paper by 'conventional oil' we generally mean conventional oil as defined above plus EOR, and also most heavy oils except tar sands and Orinoco oil; and excluding NGPLs.

A specific category of conventional oil is used by Campbell, that of 'Regular Conventional' oil; where this is conventional oil as defined above, but less Arctic oil, heavy and extra-heavy oils (defined by Campbell as oils with densities < 17.5° API), and deepwater oil from water depths greater than 500 m. This category of oil also excludes NGPLs.

And Laherrère has recently stated (private correspondence) that the term 'conventional oil' as used in the landmark Campbell and Laherrère (1998) paper: '*The End of Cheap Oil*' referred to his recall to any crude oil produced except extra-heavy oil, oil from kerogen, other extensive oil such as tars sands and Orinoco oil, and oil in traps with no water contact.

Data Sources and Reliability

- For data on annual oil production and annual average real-terms oil price this paper uses BP's *Statistical Review of World Energy*; often abbreviated '*BP Stats. Rev*.' For oil production, the *BP Stats. Rev*. says these data comprise: "*crude oil, shale oil, oil sands and* condensate *(both lease condensate and gas plant condensate). Excludes liquid fuels from other sources such as natural gas liquids, biomass and derivatives of coal and natural gas*."
- Proved reserves: Public-domain data on proved (1P) oil reserves, such as those from the EIA, OPEC, *BP Stats. Rev*., *World Oil* and *Oil and Gas Journal* should not be used for understanding past or future oil production, except as set out in Bentley (2015c). Incidentally, Campbell (2013, p6) suggests based on oil industry 2P data that for some Middle East OPEC countries the 1P oil reserves reported may be the country's *original* 2P reserves, i.e. 2P reserves before production started. This approach might be seen as defensible, as it is the basis on which oil and gas fields which cross national boundaries are allocated, and would help explain why the reserves estimates for these countries do not change.
- Proved-plus-probable (2P) reserves: These reserves data should be used instead of 1P data, and are available from a wide variety of sources, and in aggregate form from oil industry consultancies such as IHS Energy, Wood Mackenzie and Rystad Energy. In addition, Globalshift Ltd. now provides 2P data for free of oil yet-to-produce to 2100.
- Definition of URR: For conventional oil the URR is the sum of the region's cumulative production, plus the oil that has been discovered but not yet produced (the oil reserves), plus the oil expected to be found in future (the 'yet-to-find'). When the URR includes non-conventional oil its estimation is somewhat more problematic, as often the various non-conventional oil resources (such as tar sands oil, or oil from kerogen) were discovered and quantified long in the past, but only become included in a region's reserves when specific projects to extract these oils get either proposed or approved. In this case, the URR estimate generated may be especially sensitive to assumptions on future technological change and oil price. In both cases URR estimates sometimes include an estimate of the additional oil that will be produced over time due to reasonably-anticipated advances in technology, and increases in oil price.
- Estimating URR: There are a number of different ways to estimate URR, for example see Campbell and Laherrère (1998), or Annexes 4 and 5 of Bentley (2016a). These vary from 'Hubbert linearisation', which requires only past production data, to summarising future production to a distant future date based on a by-field (aggregated where individual field data are unavailable) and by-project model, combined with assumptions on future discovery and technical gain, as is done by Globalshift in the data presented in Table 2. Also, once the peak of oil *discovery* in a region is past, extrapolation of the backdated discovery trend, combined with knowledge of the petroleum geology in the region and views on future technical gain, can give robust estimates. For a detailed discussion of URR estimates and how they have influenced recent oil forecasts, see Bentley (2015a, b; 2016c). For the key mid-1990s Petroconsultants reports giving URR estimates for global oil and gas (including the non-conventionals) see Laherrère et al. (1994); Campbell and Laherrère (1995); Laherrère et al. (1996); and Perrodon et al. (1998).
- URR growth: A question arises as to how reliable are URR estimates, with for example BP *Stats. Rev.* in 2019 stating in its download on reserves definitions:
- "*Ultimately recoverable resource (URR) … is an estimate of the total amount of oil that will ever be recovered and produced. It is a subjective estimate in the face of only partial information. Whilst some consider URR to be fixed by geology and the laws of physics, in practice estimates of URR continue to be increased as knowledge grows, technology advances and economics change. Economists often deny the validity of the concept of ultimately recoverable reserves as they consider that the recoverability of resources depends upon changing and unpredictable economics and evolving technologies.*"
    - o URR estimates can certainly change over time. But for conventional oil once the peak in discovery is past URR estimates can remain remarkably static. For example, the higher of the two URRs assumed for conventional oil in the US Lower-48 by Hubbert (1956) of 200 Gb still looks about right, as US conventional oil production peaked at close to half this; and where Campbell (2013) gives 200 Gb for US 'Regular Conventional' oil. Likewise, the UK government's estimate in 1974 of 4500 Mt for UK North Sea oil is still valid today. Likewise also, as discussed above, the global URR estimate range from the 1970s to early '80 s of 1800 Gb–2500 Gb,

if perhaps on the conservative side, is still not unrealistic today.

Please see also:

- For a detailed analysis of oil data, and data providers, see Laherrère et al. (2016, 2017).
- Note that most major international oil companies are themselves past their resource-limited peak in oil production, certainly for conventional oil; see: https://crudeoilpeak.info

Volumes of Conventional Oil, Non-Conventional Oils, and Other Liquids

The world contains very large quantities of potentially recoverable oils and other liquids. The volumes of these, and their production cost ranges (in 2012 dollars), are shown in Fig. 4.

In Fig. 4 'conventional' oil can be viewed in various ways. It can be just the first three blocks on the left of the chart, giving a URR of ~ 3600 Gb; it usually includes also Arctic and ultra-deepwater oil, for a total URR of ~ 3800; or can include also EOR oil, for a total URR of ~ 4200 Gb.

For shale ('light-tight') oil, estimates of its global URR are still in flux:

- In 2016 the United States Geological Survey (USGS) estimated the global recoverable resource of shale oil to be around 750 Gb; considerably larger than the IEA 2013 estimate of ~ 250 Gb shown in Fig. 4.
- More recently, IHS Energy estimated ~ 840 Gb of light-tight technically recoverable oil in 25 'super-basins' around the world.
- The US EIA currently gives an estimate for the global unproved technically recoverable resource (UTRR) of tight oil at https://www.eia.gov/analysis/studies/worldshalegas. This gives data for 46 countries, mostly from 2013, though some data are from 2014 and 2015, for a total UTRR of 418 Gb. To this the global cumulative production and proved reserves of tight oil of ~ 35 Gb need to be added, to give a URR of ~ 455 Gb.
- Rystad's global '2PCX' estimate for light-tight oil is ~ 275 Gb, defined as the: "*Most likely* estimate [of remaining oil reserves] *for existing fields, plus contingent resources in discoveries, plus risked prospective resources in yet undiscovered fields*." (Rystad 2018). Hence adding global cumulative production of ~ 15 Gb yields a URR of ~ 290 Gb.

Put together, these estimates suggest that the world has perhaps some 400 Gb–800 Gb of potential technically recoverable resources of tight oil. But having resources is one thing, having access rights, government approval and public support to bring these on-stream is another, and where for much of the tight oil outside the US these factors are far from clear. (Moreover, much of US tight oil production has been from companies experiencing negative free cash flows from operations, and hence need increases in the price of oil to turn these cash flows positive.)

Overall, the main conclusion from Fig. 4 is that the world has still available very large quantities of potentially technically recoverable oil and other liquids, of the order of ~ 7000 Gb. This is about five times the quantity of 'all-liquids' already consumed (shown by the leftmost rectangle of Fig. 4) of ~ 1200 Gb by 2012, hence ~ 1400 Gb by 2018.

Finally we note that, except for tight oil, the quantities of technically recoverable oil by category shown in Fig. 4 have been known with reasonable accuracy for many years.

Three Sets of Global Oil Production Peak Data and URR Estimates

This section gives the data underlying approximate global URR oil estimates from Campbell, Globalshift Ltd., and Rystad Energy. Note that the categories of oil covered by these estimates differ.

Table 2 Global Oil Production Peak Data, and Estimates of Global Production to 2100/Inferred URR

(a) Data from Campbell (2013); Regular Conventional oil (see definition below)

Data until (year): 2010

Cum. prod. to 2010	Future known: 2P res'vs	Future yet-to-find	Cum. Pr. to 2100 = 'URR'	Date of peak discovery	Date of peak prodn.	% URR at 2010
(Gb)	(Gb)	(Gb)	(Gb)	(year)	(year)	(%)
1093	795	113	2000	1964	2004	55%

(b) Data from Globalshift Ltd. (End-2017); All Fossil Oil (incl. NGLs)

Data until (year): End-2017

Cum. prod. to 2017	Cum. Pr. to 2100 = 'URR'	Date of peak prodn.	Peak prodn.	% URR at 2017
(Gb)	(Gb)	(year)	(Mb/d)	(%)
1460	3249	2029	111.2	45%

(c) Data from Rystad Energy (June 2018); All Crude Oil (excl. NGPLs)

Data until (year): End-2017

Cum. prod. (G'shift) to 2017	Future known ('2P')	Future known incl. cont. ('2PC')	Future incl. cont. incl. YtF ('2PCX')	Hence YtF	Cum. Pr. to 2017 + 2PCX = 'Inferred URR'	% URR at 2017
(Gb)	(Gb)	(Gb)	(Gb)	(Gb)	(Gb)	(%)
1460	681	1229	2210	981	3670	40%

Campbell's data:

Data are from *Campbell's Atlas of Oil and Gas Depletion*, Springer, 2013.

Regular Conventional oil is conventional oil, but also excludes deep-water oil (> 500 m water-depth), Arctic oil, and heavy oil (10–17.5° API).

'Date of peak discovery' gives the year in which oil *discovery* reached its maximum, based on the backdated 2P oil discovery data in the IHS Energy 'PEPS' E&P database, but as adjusted for a number of countries as described in Campbell (2015).

Campbell approximates URR by the total *Regular Conventional Oil* that will have been produced by 2100.

Globalshift Ltd. data:

Data are from website (www.globalshift.co.uk), and as also kindly supplied by the company.

Data refer to all fossil oils, so include conventional and non-conventional oils, including 'light-tight' oils produced from artificially fractured wells, bitumen from oil sands converted to syncrude, and NGLs extracted at a refinery from gases. They exclude oil retorted from kerogen, biomass liquids, GTLs and CTLs.

Globalshift does not provide a URR but forecasts total production of all fossil oils to 2100. Here we use this to give an approximation to URR. However, depending on global circumstances post 2100, Globalshift points out that it is possible that considerably more oil may be produced after that date.

Rystad Energy data:

Data are from Rystad Energy press release dated June 15th 2018.

Data refer to "crude oil plus lease condensate", so include conventional and non-conventional oil, but exclude NGPLs.

Rystad define their categories of remaining recoverable oil as:

2P: "*Proved + Probable oil reserves,* [i.e. reflecting the] *most likely estimate in existing fields.*"

2PC: "*Proved + Probable oil reserves plus mean contingent recoverable oil resources in yet undecided projects/discoveries, including noncommercial volumes*."

2PCX: "*Most likely estimates for existing fields, plus contingent resources in discoveries, plus risked prospective resources in yet undiscovered fields*."

The press release gives no data for cumulative production to-date (though such data may be available via the company's UCubeFree database), so here, since the categories of oil covered are rather similar, we have copied across the Globalshift data for cumulative oil production to 2017

Likewise, Rystad Energy give no formal URR, so we infer this by adding their 2PCX estimate to cumulative production

Annex 2: Forecasts and Views on Future 'All-liquids' Supply

Given that global production of conventional oil will decline soon unless the price of oil goes very high, this annex summarises the current main forecasts and views on the future of 'all-liquids'. These range from seeing constraints to 'all-liquids' supply as already binding, to those that see such constraints as some distance away, to those that in essence dismiss such constraints altogether.

We recognise that the authors of these forecasts and views may see the summaries we give below as over-simple, but our purpose is not great precision in describing these but to capture their range, and hence indicate the work needed to achieve closer agreement on this important subject. We list the forecasts and views in sequence from the more concerned to the less concerned, but note that all pre-date the sharp fall in oil demand in early 2020.

Oil-Supply Constraints are Already Binding, and Will Become More so Unless Oil Demand Falls Rapidly

This forecast reflects the modelling of Campbell and Laherrère (Campbell and Laherrère, 1998; Campbell 2015; Laherrère 2015), where their models incorporate their findings that oil discovery data held in at least some of the oil industry datasets need to be reduced significantly if they are to correctly reflect proved-plus-probable (2P) oil discovery. The authors suggest this is the case for some Middle East countries, and also for FSU countries, where for the latter the oil reserves reported are ABC1, and in the view of these authors are typically 30% higher than 2P estimates.

Peak Global Conventional Oil Production is Expected Fairly Soon, and Will Likely not be Compensated by Production of All-Oil, or All-Liquids, Unless the Price of Oil is Very High

Forecasts holding this view come from a range of 'independents' (individuals and some key consultancies) including IHS CERA (Jackson and Smith 2014), Miller (2015), Rystad Energy (Wold 2015), and Globalshift Ltd. (Smith 2015). These forecasts are based on detailed bottom-up models by field and project, and use a combination of published oil news and data and oil industry commercial 2P datasets covering oil discovery, production and reserves.

This view is in part supported by the UKERC *Global Oil Depletion* study which concluded: "*On the basis of the current evidence we suggest that a peak of conventional oil production before 2030 appears likely and there is a significant risk of a peak before 2020*." (Sorrell et al. 2009). It also seems to be the view of a recent study published by the Geological Survey of Finland, based on current literature rather than on detailed modelling (Michaux 2019), and also that of two papers in this journal which forecast future regional and global oil production based on regional and country production decline curves (Dittmar 2016, 2017).

Conventional Oil Production Will Stay Roughly On-Plateau At Least Out to 2040, and There Are Plenty of Non-conventional Oils and Other Liquids That Can Come On-Stream to Meet the Expected Increase in Demand, Although This Will Require the Oil Price to Rise Significantly. Demand for Oil Is Not Likely to Fall Over This Period Unless There are Much Stronger Pressures for this Than Now

This approximates the recent forecasts (as published up until 2018) from most 'mainstream' energy forecasting organisations, including the IEA, EIA, OPEC and some oil majors.

The view that global conventional oil production can remain about on-plateau for the next 20 years or so is—we assume—based in part on the USGS estimates discussed in the context of Fig. 4 and Table 1 (though we have been told IEA's forecast reflects the expectation that a higher oil price going forward will bring on sufficient additional conventional oil to offset the decline in older fields).

We note that in the past society has been poorly served by oil forecasts from these 'mainstream' organisations, and where their recent forecasts mark a significant change from those of only a few years previously. The earlier forecasts were for adequate oil of all categories—including conventional oil—to be available to the end of their forecast horizons, and hence for the oil price to remain low. Thus almost none of the earlier 'mainstream' forecasts foresaw the sharp oil price rise that occurred from 2004 onwards, despite the many decades of explicit warnings from scientists. An exception was the IEA 1998 *World Energy Outlook (WEO)*, where Bourdaire—in charge of this forecast—understood that the global peak in conventional oil production would occur soon.[2]

We suspect that the fundamental reason for this major oversight from the mainstream forecasters was that while they correctly factored-in the total oil available (Fig. 4), they did not understand that much of this oil—the conventional oil—would peak at 'mid-point'. Past 'mainstream' forecasts are discussed in Wachtmeister (2018) and Bentley (2016a).

For analysis of the recent differences between the oil production forecast in the IEA's 2018 *WEO* and the significantly lower forecast in the 2019 edition, see: https://aspo-deutschland.de/dokumente/2019-11-21AnalysisOfWEO2019-ASPO-de.pdf.

There is No Basis for Concern About Peak Oil Supply as the World is Moving from an Era of Perceived Oil Shortage to One of Aabundance

This view (as opposed to a quantitative forecast) is that of Aguilera and Radetzki, and also of Spencer Dale of BP. Aguilera and Radetzki (2016) suggest that tight oil will add 20 Mb/d by 2035 to global oil supply, while much of the technology that opened up tight oil is also as applicable to conventional oil, and that this will add an additional 20 Mb/d by 2035. Dale likewise writes that increased production of tight oil, plus the additional conventional oil that uses tight oil technology, mean the world has now entered an era of 'oil abundance' (Dale 2015; Dale and Fattouh 2018).

However, it seems to us that these authors are again overlooking the principle of 'peak at mid-point', and simply add this anticipated extra oil to current total global production without accounting for the decline that will occur in existing fields. We know this in the case of Dale, for example, where in a lecture at Imperial College UK in December 2017 his view of 'future oil abundance' was based only on data of proved oil reserves and R/P ratios, without recognising the constraints that arise from 'peak at mid-point' (Dale 2017).

Likewise, Aguilera (2019) presents a chart of global oil and liquids recoverable vs. production cost (similar to Fig. 4 above), and says in effect: 'There is a lot of oil available at not too high a cost, so there is no reason to expect the price to rise significantly'.

Peak Oil from the Supply Side is a Myth

Though this paraphrase may overstate the case, 'peak oil is a myth' we think is still the view of authors like Yergin (2011) who wrote "*For decades, advocates of 'peak oil' have been predicting a crisis in energy supplies. They've been wrong at every turn*", and Lynch (2019), author of the 2016 book: *The Peak Oil Scare and the Coming Oil Flood*.[3]

[2] A key meeting held in 1997 at the IEA reflected two opposite views: 'a near-term peak in oil', and 'no oil constraints in sight' (see recollections by some of those present in Campbell 2011). J-M Bourdaire chaired this meeting, and endorsed the 'peak is close' view in the 1998 IEA *World Energy Outlook*. In its base case this used the then-USGS mean global URR for conventional oil of 2300 Gb, and predicted that the global peak of all-oil, except for 'unidentified unconventional' oil, would occur in 2014. Bourdaire later made it clear that 'unidentified unconventional' was intended to signal the expectation of an all-oil peak. In the event US tight oil became this 'unidentified unconventional'. In 1998 there had been considerable push-back against the IEA making any mention of peak oil, and a similar situation occurred with the IEA 2008 *WEO* under Birol, see Chapter 29 of Auzanneau (2018).

[3] One of us (Bentley) has had a number of communications with Dale, his predecessor as Chief Economist at BP, Peter Davies, with Aguilera and also Lynch. None of these communications seems to have altered the views of any of those involved, including Bentley.

Global Demand for Oil Will Fall Well Before Any Supply-Driven Peak Occurs

Finally, there is an increasing number of organisations which state that global supply-side constraints for oil are not a concern, as they forecast instead a relatively near-term peak in the global *demand* for oil. The main drivers at play in such forecasts are society's thirst for oil, changes in society, and the need to meet climate change goals. We discuss these ideas in turn:

Society's Thirst for Oil

Oil is the world's largest commercial source of energy, and provides the crucial transport that underpins nearly all of global agriculture, industry and commerce, and thus supports nearly all of current economic activity. In addition, oil is used extensively in some counties for heating and the generation of electricity, and globally in the production of petrochemicals. Each year the world consumes some 36 Gb of all-liquids; if put into a line of 50-gallon drums this would circle the earth over 400 times.

In addition to current demand, nearly all political leaders look to increasing quantities of energy (including oil) to support the growing populations and rising expectations of standards of living of their electorates.

And, as a direct corollary of oil's key role in society, citizens often get angry if they see the price of fuel rise sharply, whether this be the 'fuel protests' across much of Europe in 2000 triggered by a jump in the cost of fuel, the *gilets jaunes* protests in France triggered by a fuel tax rise for climate change reasons, or the many cases where governments realise how much of their exchequer goes to fuel subsidies (sometimes as pointed out by the IMF), and sharply raise the price of fuel, as in Ecuador and Iran in 2019.

In summary: currently there is a deeply embedded global economic dependence on oil, and a general expectation of significant additional quantities becoming available at not too high a price.

Changes in Society

But society is changing, and perhaps the demand for oil also. Many in cities in the richer countries are no longer demanding their own vehicles, preferring instead to travel by ride-hailing apps, public transport, foot or bicycle. More recently still, there has been significant pressure from both activists and governments to reduce pollution levels in cities, particularly of NO_x and particulate matter, and this is affecting the use and choice of vehicle type in towns, leading also to a potential reduction in demand for oil. And perhaps the world may use the opportunity of the pandemic to re-invent its requirement for oil-fuelled transport.

Reduction in Oil Demand to Meet Climate Change Goals

But the biggest reason to reduce oil use comes from climate change where it is now clear that fossil fuel use (including oil) must soon decline if the agreed target of an average global surface temperature rise of 2 ºC above pre-industrial is to be met; and more so if this target is 1.5 ºC above. On the quantity of oil that must then be left in the ground, see for example McGlade and Ekins (2015).

Peak Demand?

So, the question becomes: Does the world reach peak demand for oil before peak supply?

To examine this we need to differentiate two kinds of peak demand. The first we term 'exogenous' peak demand, driven by some mix of the social change and climate change pressures listed above. The other is 'supply-driven' peak demand, where demand indeed falls, but driven now by high oil prices, in turn reflecting limits to supply. In practice, and given what we have set out above on likely constraints to oil supply, both types of 'peak demand' may occur in combination, and it may take considerable analysis from economists and others to disentangle the two.

Quite a number of organisations are now forecasting the global peak in demand for oil in the relatively near term, and hence, implicitly or explicitly, forecasting that this peak will come before a supply-constrained peak. These organisations include Citi Bank, Bank of America Merrill Lynch, World Energy Council, DNV-GL, Carbon Tracker and others.

We have not so far had the opportunity to examine these forecasts in detail, so cannot comment usefully, except to say that we assume these organisations are unlikely to have factored into their forecasts the oil supply constraints detailed in this paper. In this context, we note that the IEA in its 2019 *World Energy Outlook* Base Case says that while global passenger vehicle demand for oil may peak within 10 years, the total global demand for oil (which includes trucks, shipping, aviation cargo and petrochemicals) will likely not reach plateau until around the 2030s.

Summary

Taken together, the above is an extraordinarily wide range of forecasts and views on global future oil supply, coming as they do from reputable, widely-quoted organisations and individuals. Given the current critical importance of oil supply to the global economy, it seems to us there is an urgent need to move towards a measure of agreement.

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