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Current Opinion in Environmental Sustainability

Future world oil production: growth, plateau, or peak?

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With the exception of two oil shocks in the 1970s, world oil production experienced steady growth throughout the 20th century, from about 400,000 barrels a day in 1900 to over 74 million by 1999. Conservative projections from the International Energy Agency for 2035 suggest that production will increase to about 96 million barrels a day. If this target is met, world oil production will have exceeded 2000 gigabarrels (billion barrels) in the span of 135 years. Almost all of the oil products humans consume are derived from sources that are non-renewable. With this in mind, this paper considers how long world oil production can continue to grow or if it will eventually plateau or peak and then decline. The paper concludes with the observation that whether peak oil has already occurred or will not occur for many years, societies should be prepared for a world with less oil.

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Current Opinion in Environmental Sustainability 2011, **3**:225–234

This review comes from a themed issue on Energy Systems
Edited by Shonali Pachauri and Aleh Cherp

Received 1 July 2010; Accepted 18 May 2011

1877-3435/$ – see front matter

DOI 10.1016/j.cosust.2011.05.001

Introduction

Energy is central to the economic and social wellbeing of any society. Of all the primary energy sources available to mankind, three are dominant: oil (33.2% of world's total energy demand), coal (27.0%), and natural gas (21.1%) [1]. Refined oil products (or liquids), with their high energy density, ease of transport, and capacity to be used in any modern energy service (transportation, heating and cooling, and electrical generation), are the most versatile. The importance of oil to the world's economy cannot be overemphasized; not only does it meet almost all of the world's transportation energy needs [1] but also its byproducts can be used as a feedstock for the petrochemical industry (T Ren, Petrochemicals from oil, natural gas, coal and biomass: energy use, economics and innovation, PhD thesis, s.l.: Utrecht University, Netherlands, 2009, http://igitur-archive.library.uu.nl/dissertations/2009).

As Figure 1 shows, the first seven decades of the 20th century witnessed the unprecedented and exponential growth in the production of oil, doubling roughly every 10 years, from 435,000 barrels per day in 1900 to over 48 million barrels per day in 1970. The rise in production was interrupted twice, in 1975 and then in 1980, attributable to the two oil 'shocks' that reduced oil supply and increased its price 10-fold [2–4]. Despite the shocks and subsequent commitments by western governments to reduce their energy intensity [5], the growth in oil consumption, and hence production, resumed in the mid-1980s, albeit in a more linear fashion. By the end of the century, world oil production had reached almost 74 million barrels a day.

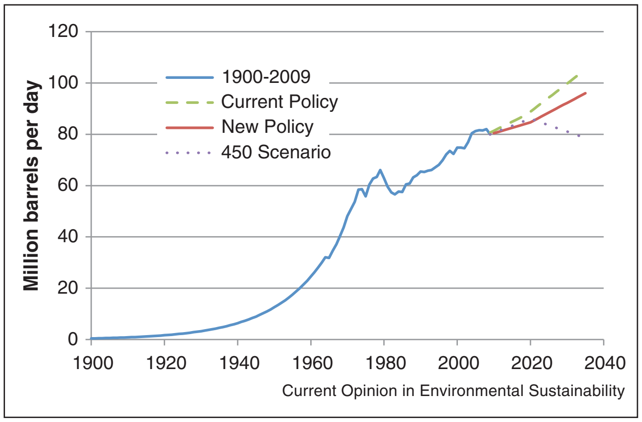
Increasing demand for oil from China and other emerging market economies pushed world oil demand higher in the early years of the 21st century; by 2008, the world was producing about 82 million barrels of oil a day [3].

The International Energy Agency's World Energy Outlook 2010 presents three future energy scenarios to 2035. Table 1 summarizes the three oil-related scenarios. Future production is expected to be driven largely by the growing demand from non-OECD countries. Demand from OECD countries is expected to stabilize because of its aging population and increasing use of non-liquid fuels for energy services that presently use oil products [8].

Regardless of the scenario, by 2035, over the past 135 years, the world will have produced over 2000 gigabarrels (billion barrels) of oil. There are, not surprisingly, environmental consequences associated with producing this much oil. Like all other hydrocarbon fuels, oil emits carbon dioxide when combusted; between 2008 and 2035, carbon dioxide emissions from oil combustion are expected to increase anywhere from 13% to 57% over 1990 levels [7]. One widely discussed approach to reducing CO_2 emissions is carbon capture and storage [9]; how applicable this will be to oil is unclear, as its principal use is expected to be transportation rather than stationary combustion.

In addition to the environmental impacts of consuming this amount of oil, it is important to consider where the oil comes from and whether there are limits to the amount of it that can be produced. The remainder of this paper considers the state of the world's oil supply, the question of when production will reach a maximum and start to decline, and possible responses to the decline.

Figure 1



World oil production: estimated (1900–1964 [5]), actual (1965–2008 [2]), and IEA projections (2009–2035) [6]. (The IEA's World Energy Outlook 2010 presents three energy-future scenarios: current policy (no changes in world energy policies developed and announced as of mid-2010), new policies (applies broad policy announcements that have been announced and include pledges to reduce greenhouse gas emissions and phase out fossil-energy subsidies, and 450 scenario (sets out an energy pathway intended to limited global temperature rise to 2°C by limiting atmospheric CO_2e concentrations to 450 parts per million). The IEA's 2035 oil production forecast is for the most part, in keeping with that of the Energy Information Administration 2010 International Energy Outlook, which presents three production scenarios for 2035: 89.5, 106.5, and 119.8 million barrels a day, for high-oil price case, reference case, and low-cost-oil price case, respectively [70]. Projections to 2030 from Exxon-Mobil (104 million barrels a day [71]) and OPEC (105.9 million barrels a day [72]) are within the IEA's forecast as well.)

Sources of oil

The world's liquid fuels come predominantly from reserves of fossil-energy: conventional sources or 'crude oil' (usually defined as fields that produce light and medium crude oil), non-conventional sources (heavy oils, tar sands, and shale oil), and natural gas liquids (NGLs) (the liquid component of natural gas) [10]. Liquid fuels are also derived from biological (i.e. potentially renewable) sources, but these are normally omitted from discussions relating to the extraction of oil from fossil-energy sources.

Presently, more than 85% of the world's oil production comes from conventional sources, while the remainder is predominantly from NGLs [7,11]. In a conventional field, production is ramped up to a plateau and maintained at this level until primary (natural pressure), secondary (pumps to maintain flow), and tertiary/enhanced (chemicals or other techniques to encourage flow) recovery methods have been exhausted and production declines [12].

Any oil production can be affected by 'below-ground' (the geology of the field) factors as well as 'above-ground' (politics, economics, and corporate objectives) factors. As the volume of conventional oil from existing oil wells declines because of below-ground or above-ground reasons, other sources must be found. For example, in the 1970s, production from the newly discovered oil fields of Prudhoe Bay in Alaska and the North Sea meant that western countries were no longer at the mercy of the Organization of the Petroleum Exporting Countries (OPEC). More recently, declining onshore production has forced international oil companies such as BP, Exxon-Mobil, and Shell to drill offshore in deep (300–1500 m) and ultra-deep (more than 1500 m) locations in order to maintain their production levels because they are not welcome in a number of oil-producing countries due, in part, to the rise of resource nationalism [13,14]. The offshore has allowed some countries to maintain or even increase their domestic production of conventional oil (Angola, Brazil, Nigeria, and the United States are all reliant on the offshore to meet a growing percentage of their oil production [15]). It is reasonable to assume that before April 2010, few people gave offshore oil production much thought; however, the blowout of BP's Macondo exploratory well in the Gulf of Mexico highlighted the human and environmental risks — and consequences — associated with deepwater drilling [16]. One of the last regions available for exploration and potential production is the Arctic where the melting of the polar ice is resulting in many countries pursuing national strategies to explore and exploit whatever fossil-energy sources may be found [17,7].

NGLs or 'wet' gas, a byproduct of the extraction of natural gas, are another fossil-energy source that can be used in the production of liquid fuels. There is an increasing supply of NGLs in the United States because of the growing reliance on shale gas — a natural gas that is particularly rich in NGLs [18].

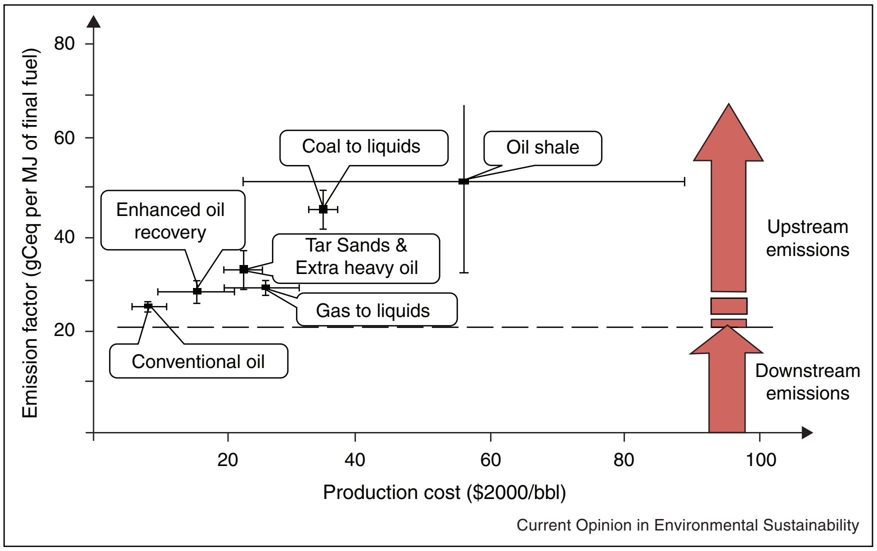
In addition to conventional sources of oil and NGLs, there are also non-conventional (or unconventional) ones.

Table 1

World Energy Outlook 2010 scenarios for oil production in 2035 [8].

Scenario	World oil production (million barrels/day)	Total oil consumption 1900–2035 (gigabarrels)	Greenhouse gas emissions (Mt)	Percentage increase over 1990 levels
Current policy	104	2082	13,782	57%
New policy	96	2044	12,628	43%
450 scenario	78	2000	9944	13%

Figure 2



Production costs and emissions for various conventional and non-conventional sources (from [27]).

These energy sources are feedstocks to a variety of conversion processes that produce a liquid fuel that can be used with or in place of conventional oil. Canada's tar sands and Venezuela's heavy oils are examples of non-conventional oil sources. The tar sands are being mined for their heavy crude and bitumen in an effort to replace Canada's dwindling supplies of conventional sources of crude oil. The water and energy required to produce a barrel of synthetic crude — and the associated greenhouse gas emissions — go well beyond those of conventional oil production [19].

Coal-to-liquid (CTL) is another example of a non-conventional oil source. The technology is often used in jurisdictions with limited access to oil-derived liquid fuels and is energy intensive; meaning that using coal as the energy source of the process will produce more greenhouse gases [20,21]. Another non-conventional source is natural gas. It is a cleaner fuel that can be converted to methanol for use as a transportation fuel [22]; although some sources of natural gas, such as shale gas or coal-bed methane in the United States, are not without their environmental impacts [23].

Many governments envisage the use of biologically derived liquid fuels from feedstocks such as algae, woody and waste biomass, and agricultural biomass for transportation purposes. There are challenges associated with each of these potential replacement fuels, including social (the use of agricultural land for food rather than fuel), economic (the costs of subsidies for biological fuels), environmental (the destruction of equatorial regions for sugar cane and palm oil and the removal of 'waste' biomass from forests), and energetic (biological fuels such as ethanol do not have as high an energy density as petroleum) [24•]. Despite these challenges, a number of organizations are expecting biofuels to make a significant contribution to world liquid fuel supply. For example, the IEA is projecting that biofuels will meet between 3% and 10% of the world's liquid biofuels demand by 2035 [7], the OECD expects about four percent of the world's total energy demand to be met from liquid fuels (including the use of 'second generation' cellulosic biofuels that offer the promise of not using food products for fuel) by 2050 [25], while an EU biofuels project expects 80% of the EU's transportation to come from biological sources in 2050 [26].

Although the end product may be the same, there are two significant differences between the production of conventional and non-conventional oil sources. The first is the cost of production; because of the additional processing costs, non-conventional energy sources typically have a lower EROI or energy return on investment. Some of these differences are shown in Figure 2.

Both conventional and non-conventional energy sources require some form of energy input in order to produce them; this can be referred to as an energy return on *energy* investment or EROEI. In the 1930s, finding and producing conventional crude oil in the United States had an EROEI value of more than 100; by 1970 it had declined to 30; recent estimates for production from new conventional crude oil wells put the EROEI value as low as 11 [28]. For non-conventional sources of oil, the EROEI values for Canada's tar sands are about six [29], while for biofuels, it ranges from less than 1 (according to corn ethanol opponents) to as high as 3.2 (according to biodiesel proponents) [30]. In all cases, the non-conventional EROEI is considerably less than that of conventional EROEI because of the energy needed in the conversion process.[a]

For more than a century, discoveries of new conventional oil fields and the development of new technologies for the production of both conventional and non-conventional oil have ensured ever increasing world oil production. The challenge facing the oil industry is how to increase production when existing fields are experiencing depletion rates of 5% or more while annual demand for oil is expected to increase at rates exceeding 1% [7]. One can argue that what is being experienced today is no different from what has happened in the past — the oil is there to be discovered, given sufficient investment and technological advances, such as horizontal drilling and tertiary extraction techniques. While there may be truth to this statement, the oil industry is being forced to look for conventional oil in locations that are both risky and more expensive, such as deep and ultra-deepwater and the Arctic [31], and non-conventional sources, notably Canada's tar sands, that are expensive, energy intensive, and damaging to the environment [32].

Peak oil

Since all sources of oil derived from fossil sources are non-renewable, oil production cannot be sustained indefinitely. This simple fact has many people claiming that world oil production has reached or is about to reach the point at which the production from a particular oil-producing region — in this case, the world — is at its maximum or peak and will begin to decline. This is referred to as *peak oil*.

Claims that a particular jurisdiction has reached its peak production capacity have been made by many people over the past 150 years — most have been proven wrong [33]. Probably the most significant exception was Marion King Hubbert's prediction in 1956. Hubbert, a geophysicist working for Shell in the United States, predicted that crude oil production in the United States would peak around 1970 [34]. Hubbert based his prediction on the time of discovery and production from oil fields, the volume of crude oil extracted, and an estimate of the ultimate recoverable resource (URR); from this, he assumed that oil production would peak when half of the resource had been extracted, producing a bell curve (a symmetric logistic curve) now referred to as Hubbert's curve [35].

At the time, Hubbert was ridiculed; however, in 1970, oil production in the lower 48 states peaked at 10 million barrels a day [36]. Although production from Prudhoe Bay in Alaska did raise US production slightly, it has been in decline since 1972 [3]. Hubbert's success in predicting the US oil peak gained him a significant following and his prediction that world oil production would peak around 2000 focused many minds, including that of President Carter who spent much of his presidency warning Americans of the dangers of energy profligacy and oil dependency (e.g. see [5,37]).

Despite being proven wrong for his prediction of a global oil peak in 2000, many of Hubbert's supporters argue that he would have been right had the world not experienced the downturn in demand caused by the oil shocks of the 1970s [38••]. Hubbert's method is far from perfect and has numerous constraints, such as knowing discovery dates, backdating apparent 'new' discoveries to the discovery date of the original field, and requiring that production is free of political manipulation [38••].

The shortcomings of Hubbert's method are one of a number of reasons why critics dismiss peak oil [39]; however, there are other techniques being employed to examine the world's oil reserves in order to find when oil production will peak [40]. For example, most of the world's oil is produced from a limited number of super-giant fields, many of which are more than 50 years old and are in decline; the cumulative effects of these declines, when coupled with information on new projects give an indication of future production [41].

One of the most comprehensive studies on peak oil literature was completed in 2009 by the UK Energy Research Council; it suggests that a peak in conventional oil production by 2030 is likely and that there is a significant risk of the peak occurring before 2020 [42••]. A list of the individuals and organizations that project a peak before 2030 is shown in Table 2, while those that do not project a peak before 2030 are shown in Table 3.

The IEA's projection for world oil production is shown in Figure 3 and is divided into NGLs, non-conventional oil, and crude oil. Crude oil is further divided into currently producing fields, fields yet to be developed, fields yet to be found, and additional enhanced oil recovery. NGLs and non-conventional oil show steady growth, whereas crude oil production essentially remains flat. Peak oil is averted by the fields yet to be found — if they are not found and there is insufficient production of NGLs or non-conventional oil, a plateau or a peak will have occurred sometime between 2020 and 2030 [43].[b]

[a] EROEI can be misinterpreted to mean that the energy input is oil, implying, for example, that 1 barrel of oil is required to produce 3.2 barrels of biodiesel. This need not be the case. However, energy still is needed; for example, steam from natural gas is employed to liquefy and extract bitumen from Canada's tar sands; in order to use natural gas for other services an approach being given serious consideration is produce steam from a fleet of nuclear reactors [29].

[b] There appears to be a growing body of evidence that world conventional oil production has reached a plateau, as suggested by the IEA in Figure 3. Another example is that the recent increases in production (and profits) by companies such as Exxon-Mobil have not come from crude oil but rather natural gas [73].

Table 2

Selected forecasts of global oil production, made between 1956 and 2005, which gave a date for the peak [69]. Pr: probable; Cv: conventional; Ncv: non-conventional; xN: excluding natural gas liquids.

Date	Author/group	Hydrocarbon	Ultimate (Gb)	Date of peak
1956	Hubbert	Cv oil	1250	'About the year 2000' (at 35 Mb/day)
1969	Hubbert	Cv oil	1350; 2100	1990 (at 65 Mb/day); 2000 (at 100 Mb/day)
1972	ESSO	Pr Cv oil	2100	'Increasingly scarce from ~2000'
1972	Report: UN Conference	Pr Cv oil	2500	'Likely peak by 2000'
1974	SPRU, UK	Pr Cv oil	1800–2480	No prediction
1976	UK DoE	Pr Cv oil	na	'About 2000'
1977	Hubbert	Cv oil	2000	1996 If unconstrained logistic; plateau to 2035 if production flat
1977	Ehrlich *et al.*	Cv oil	1900	2000
1978	WEC/IFP	Pr Cv oil	1803	No prediction
1979	Shell	Pr Cv oil	na	'Plateau within the next 25 years'
1979	BP	Pr Cv oil	na	Peak (non-communist world): 1985
1981	World Bank	Pr Cv oil	1900	'Plateau — turn of the century'
1992	Meadows *et al.*	Pr Cv oil	1800–2500	No prediction
1995	Petroconsultants	Cv Oil (xN)	1800	About 2005
1996	Ivanhoe	Cv oil	~2000	About 2010 (production mirrors discovery)
1997	Edwards	Pr Cv oil	2836	2020
1997	Laherrère	All liquids	2700	No prediction
1998	IEA	Cv oil	2300	Ref. case 2014
1999	USGS	Pr Cv oil	~2000	Peak ~2010
2000	Bartlett	Pr Cv oil	2000 and 3000	2004 and 2019, respectively
2002	BGR	Cv and Ncv oil	Cv: 2670	Combined peak in 2017
2003	Deffeyes	Cv oil		~2005 (Hubbert linearization)
2003	Bauquis	All liquids	3000	Combined peak in 2020
2003	Campbell — Uppsala	All hydrocarbons		Combined peak ~2015 (includes gas infrastructure constraints)
2003	Laherrère	All liquids	3000	
2003	Energyfiles Ltd.	All liquids	Cv: 2338	2016 (if 1% demand growth)
2003	Energyfiles Ltd.	All hydrocarbons		Peak ~2020 (includes gas infrastructure constraints)
2003	Bahktiari	Pr Cv oil		2006–2007
2004	Miller, BP: own model	Cv and Ncv oil		2025 all possible OPEC production used
2004	PFC Energy	Cv and Ncv oil		2018 (base case)
2005	Deffeyes	Cv oil		2005 (Hubbert linearization)

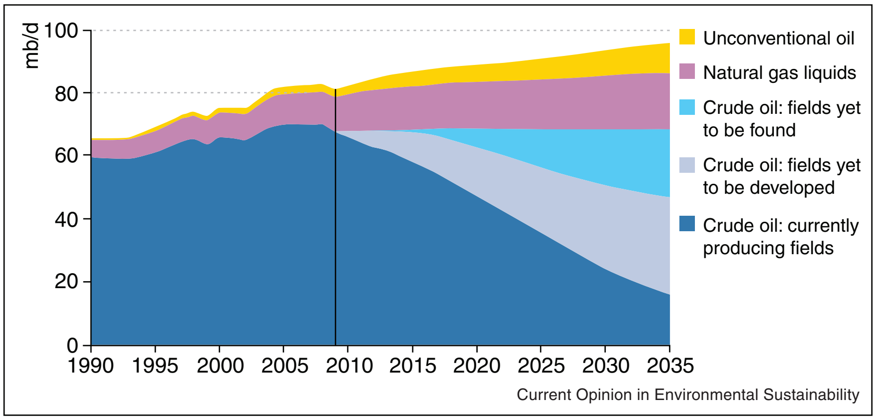
Table 3

Selected forecasts of global oil production that forecast no peak before 2030 [69]. Cv: conventional; Ncv: non-conventional; +N: plus natural gas liquids.

Date	Author/group	Hydrocarbon	Ultimate (Gb)	Forecast date of peak (by study end-date)	World production	
					2020	2030
1998	WEC/IIASA-A2	Cv oil		No peak	90	100
2000	IEA: *WEO 2000*	Cv oil (+N)	3345	No peak	103	n/a
2001	US DoE EIA	Cv oil	3303	2016/2037	Various	Various
2002	US DoE	Ditto		No peak	109	n/a
2002	Shell Scenario	Cv and Ncv oil	~4000	Plateau: 2025–2040	100	105
2003	'WETO' study	Cv oil (+N)	4500	No peak	102	120
2004	Exxon-Mobil	Cv and Ncv oil		No peak	114	118
2005	IEA: *WEO 2005*					
	Reference Sc.	Ditto		No peak	105	115
	Deferred Invest.	Ditto		No peak	100	105
2007	IEA: *WEO 2007*					
	Reference Sc.	Ditto		No peak	–	116

There is limited publically accessible information on the current state of the world's oil resources. Much of the problem lies with the fact that many Middle Eastern oil producers keep their reserve data secret [11••]. Moreover, there are instances of misrepresentation of data [44]. There have been attempts at making the data public; however, to date there has been little success [45]. Having clear accurate data, publicly available, may enable jurisdictions to develop long-term energy policies.

Figure 3



The IEA's world oil production by source (from [8]).

The peak oil debate

Given the importance of oil and the stakes involved, there is, not surprisingly, a debate surrounding the issue of peak oil. Central to the debate is the total volume of crude oil that can be extracted (i.e. the URR). Although most people involved in the debate can agree upon the amount of crude oil that has been consumed to date and the amount of crude oil that is currently being produced, there is — as the columns marked 'Ultimate' in Tables 2 and 3 show — no consensus as to how much crude oil can ultimately be recovered.

Those who argue that a peak in crude oil production is inevitable and, if it has not occurred yet, will occur soon, cite a number of factors that support their argument; all are based on the observation that all oil fields eventually peak. One approach is to sum the existing known world crude oil reserves (such as those published in the BP Statistical Review of World Energy) and to treat this as the URR; from this, a peak in crude oil production can be estimated. More advanced approaches include considering the output from existing oil-producing regions and comparing them with historical production from other regions; by applying curve-fitting techniques, an estimate of total potential production can be obtained for any field [41]. With the URR known, a peak can be determined using any of a variety of logistic curves.

However, the overreliance on URR on the basis of selective or limited data when determining the imminent date of the peak has caused many opponents of peak oil to dismiss the use of curve-fitting outright [46]; furthermore, there is a failure to understand the limitations of curve-fitting techniques such as the Hubbert curve used by many proponents of peak oil [47].

On the other hand, those who question the arguments surrounding the likelihood of an imminent peak in world oil production often point to the fact that despite the effects of depletion, world oil reserves continue to increase in size. Reserve growth is driven by various factors, including the reevaluation of oilfield production data and, perhaps most importantly, rising oil prices. Higher prices are encouraging the development of new technologies, such as horizontal drilling, which allows a producer to extract crude oil from smaller, harder to access, fields. Similarly, new technologies for enhanced oil recovery are extending the production-lifetime of existing fields and returning old, abandoned fields to production [48].

There exist a number of counterarguments to the seemingly unstoppable growth in both production and reserves. First, many of the new discoveries typically have high depletion rates, limiting their long-term production [7]. Second, these discoveries are much smaller than the giant fields discovered in the early and mid part of the 20th century [42••]. Third, a growing number of new fields are in harsh environments, such as offshore, ultra-deep fields in Brazil or in the Arctic Ocean, making production riskier and more expensive [7].

Of course, a plateau or peak in world oil production need not be limited by the URR, other factors could be at play, both above ground (lack of investment in oil exploration [7], environmental legislation banning or limiting drilling, conflicts in oil-producing regions [49]) and below ground (depletion of giant and super-giant oilfields, the availability of energy and water for non-conventional oil production, the failure of natural gas to meet the production targets many are predicting [50]).

Regardless of when or why the plateau or peak in world oil production occurs, the challenge will be ensuring energy security, the 'uninterrupted physical availability [of energy] at a price which is affordable, while respecting environment concerns' [51].

Accommodating future demand

Over the past century, much of the world has become dependent on oil. Infrastructure has been designed that supports long-term oil availability and short-term accessibility of widely acceptable and affordable oil products [52,53]. As more of the world's population becomes (or wants to become) dependent on oil, growth in oil production is necessary. However, should production reach a plateau or a peak, availability, accessibility, and affordability may quickly become a thing of the past as demand cannot be satisfied [54,55].

Preparing for a plateau or a peak in world oil production will be a long-term activity potentially requiring considerable changes in the way a jurisdiction uses energy [56]. Ideally, this would be a worldwide activity, much like the IEA's Coordinated Emergency Response Measures (CERM) for major international oil disruptions which, amongst other things, allows sharing of available supplies between member countries [57]. Alternatively, Campbell's oil depletion protocol that ensures fair and equitable access to oil products during a time of oil depletion could be employed [58]. However, without international agreements the impact would not be felt uniformly across the world. For example, wealthy individuals and jurisdictions would be less affected by access and affordability issues, potentially protected by bilateral agreements between suppliers and consumers, while those without such protection will be vulnerable to the effects of energy poverty [7]. The impact of the plateau or peak on a jurisdiction will depend in part on how reliant it was on oil [59].

Actions to address a plateau or peak fall into one of reduction (reducing energy use through conservation or gains in energy efficiency), replacement (replace existing sources of oil with other secure sources of liquid fuel), and restriction (restrict new energy demand to energy sources other than oil) [60].

Of the three actions, restriction may be the most important as there will be a need for energy sources that enable the movement of goods and people. Restricting future energy consumption to non-liquid fuels will require a change in the energy sources and infrastructure now used to meet the demand currently satisfied by liquid fuels. Ignoring aviation, there are essentially two contenders at present: natural gas and electricity, while hydrogen is seen as something in the more distant future. Large-scale adoption of natural gas in gas-poor regions of the world will require more infrastructure in the form of pipelines or liquefied natural gas (LNG) liquefaction and regasification facilities to meet both existing and new demand. However, the lack of investment, domestic demand in the exporting country, and geopolitical tensions can all contribute to natural gas shortages in importing countries [61,62]. While future natural gas supplies may be sufficient to meet existing natural gas demand, the degree to which production can be increased to meet the needs of energy services currently using oil products is unclear.

Given sufficient supply and the proper storage facilities, future demand for energy in transportation and heating and cooling could be restricted to electricity. Whether enough environmentally sustainable supply can be found is an issue that must be addressed with countries such as China and the United States planning to maintain or expand their reliance on coal for electrical generation [63,64]. One method of increasing electrical supply without new capacity is to reduce grid losses while using spare capacity to meet the demand from interruptible loads [65]. Although renewables such as wind are often maligned because of their intermittency, by making the load 'follow' the supply (as opposed to today's approach of having the supply follow the load), renewable electricity can be used more effectively [66].

Although many of the methods proposed to address declining world oil supply are driven by the need to ensure energy security, some of them could have serious consequences for the environment in general and the climate in particular.

Declining world oil supply, energy security, and climate change

At first glance, a decline in world oil supply would appear to be an energy security problem that most oil importing jurisdictions will be facing sooner or later. Such a decline could be seen as beneficial to the environment in that a decline in combustion of oil products should mean a reduction in greenhouse gas emissions. However, this need not be the case, as the loss of availability or accessibility can provide investors with the confidence to finance activities such as the exploitation of coal and non-conventional resources (e.g. CTL and tar sands and oil shale extraction) as a replacement for existing oil products, potentially offsetting any environmental benefits [67].

In order to mitigate climate change, policies must be implemented to reduce greenhouse gas emissions while maintaining energy security — one cannot be addressed without the other. Volatile energy markets affecting the availability and affordability of liquid fuels can directly affect a jurisdiction's energy security and hence its climate policy [68]. This double-edged sword suggests that energy security and climate change are potential co-beneficiaries of proactive energy policies. Preparing for peak oil and ensuring the energy services currently supported by oil products will need to accommodate both energy security and climate change challenges; solutions that are environmentally sustainable and able to maintain a reliable and affordable supply of energy services.

Concluding remarks

Oil has transformed the world. Plastics and aviation are but two of a myriad of goods and services that oil has permitted. This is not to say that humanity's use of oil has been faultless: spills, blowouts, and emissions are all the results of the widespread and virtually unrestricted use of oil. As the world's population has become more dependent on oil products, the possibility of shortages or price increases, or both are viewed with grave concern by politicians and the public alike.

In the past, crude oil was simply something that was relatively easily extracted from the ground and refined. Over time this has changed, not only is crude oil becoming harder and more expensive to produce but also with the rise of resource nationalism, it is no longer the exclusive domain of western international oil companies. This, and the demand for greater environmental regulations in many developed countries, have spawned the development of technologies to increase the production from abandoned oil fields, as well as making fields that were once ignored because of their size, suddenly much more attractive. Furthermore, exploration is moving into the oceans and Arctic to search for other sources of crude oil — at a greater expense.

There has also been a rise in the use of non-conventional oil sources, such as Canada's tar sands and Venezuela's heavy oil, to help offset the seemingly limitless growth in the demand for oil. Unlike conventional oil sources, non-conventional sources are both more expensive and more energy intensive — adding to the cost of the oil produced and to the environmental impact. The earth is finite; thus the sources of conventional and non-conventional oil are finite as well. Liquid fuels derived from fossil sources have transformed the world — whether this growth can continue will influence energy security and climate change policies in every jurisdiction.

Data from a variety of sources suggest that the world's production of conventional oil has reached a plateau, but the combined production of conventional, NGLs, and non-conventional oil is still rising. As production from conventional oil fields begins to decline, there is literally a race taking place to find new sources of conventional crude to offset these declines. If sufficient crude oil is not found, total world oil production will plateau and eventually peak, leading to accessibility and affordability issues for many people.

Addressing the plateau and peak will require a reduction in the amount of oil (and energy in general) the world consumes. There will be a need for liquid fuels that can replace existing sources of oil and the development of new energy sources and technologies that restrict new demand to sources other than oil.

Technological advances, such as deepwater and ultra-deepwater drilling, hydraulic fracturing (or frac'ing) to obtain shale gas, horizontal drilling, enhanced oil recovery, tar-sands extraction techniques, the ability to drill in the Arctic, and advanced biofuel production techniques will all contribute to the URR. However, most of these technologies are energy intensive, costly, and potentially polluting and are expected to do little more than delay a plateau or peak by more than a few years.

Accommodating the increasing future demand for secure supplies of liquid fuels while minimizing its impact on the climate will require energy policies to be developed that address both energy security and climate change, thereby achieving mutually reinforcing benefits. It is no longer a case of 'if' or 'when' there will be a plateau and eventual peak in world oil production, it is now a question of how jurisdictions can prepare for a world with less oil, one in which energy security and climate policy play a dominant role.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. IEA: *Key World Energy Statistics 2010*. Paris: International Energy Agency; 2010.

2. Hirsch RL, Bezdek R, Wendling R: **Peaking of world oil production and its mitigation**. In *Driving Climate Change: Cutting Carbon from Transportation.* Edited by Sperling D, Cannon JS. s.l.: Academic Press; 2007:**9-27**.

3. BP: *BP Statistical Review of World Energy*. London: BP plc; 2009.
BP's *Statistical Review of World Energy* is widely cited and is a useful source of data. Its major shortcoming is that it relies on unverified government data. Data from the Energy Information Administration (e.g. 9, 16, 19, 58, 65, and 71) are always helpful, as is that from the International Energy Agency (e.g. 1 and 8). Regrettably, budget cuts in the United States' government mean that the EIA has ceased publishing the International Energy Outlook.

4. Economagic: *Price of West Texas Intermediate Crude; Monthly NSA, Dollars Per Barrel*. Economagic.com: Economic Time Series Page [online] n.d. [cited: June 30, 2010] (http://www.economagic.com/em-cgi/data.exe/var/west-texas-crude-long).

5. Horowitz D: *Jimmy Carter and the Energy Crisis of the 1970s — The ''Crisis of Confidence'' speech of July 15, 1979*. s.l.: Bedford/St. Martin's; 2005:. ISBN: 0-312r-r40122-1.
(Daniel Horowitz) and 38. (Kevin Mattson) give sobering accounts of President Jimmy Carter's attempts at informing the American public of the energy challenges they were facing in the late 1970s. Had they listened, things may have been very different now.

6. Caruso G: *When Will World Oil Production Peak?* [online] June 13, 2005 [cited: June 26, 2010] (http://www.blacksandspetroleum.com/reportusa.pdf).

7. IEA: *World Energy Outlook 2010*. Paris: International Energy Agency; 2010:. ISBN: 978 92 64 08624 1.

8. EIA: *International Energy Outlook 2009*. Washington: Energy Information Administration; 2009.

9. Johnsson F, Reiner D, Itaoka K, Herzog H: **Stakeholder attitudes on carbon capture and storage: an international comparison**. *Int J Greenhouse Gas Control* 2010, **4**:410-418.

10. Bentley R, Miller R, Wheeler S, Boyle G: *UKERC Review of Evidence for Global Oil Depletion — Technical Report 7:*

Comparison of Global Oil Supply Forecasts. s.l.: UK Energy Research Council; 2009:. REF UKERC/WP/TPA/2009/022.

11. •• Simmons M: *Twilight in the Desert: The Coming Saudi Oil Shock and the World Economy*. s.l.: Wiley; 2005:. 0-471-73876-X.

The late Matt Simmon's *Twilight in the Desert* is an interesting analysis of why Saudi Arabia may well have reached the peak of its production capacity. The description of the oil industry and the history of giant and super-giant oil fields are extremely well done.

12. Babadagli T: **Development of mature oil fields: a review**. *J Petrol Sci Eng* 2007, **3–4**:221-246.

13. Gold R, Davis A: **Oil officials see limit looming on production**. *Wall Street J* [online] November 19, 2007 [cited: June 28, 2010] (http://online.wsj.com/article_print/SB119543677899797558.html).

14. Knovel: In *Handbook of Offshore Engineering*, vols 1–2. Edited by Chakrabarti SK. Amsterdam: Elsevier; 2005**. ISBN: 978-0-0805-2381-1**.

15. EIA: *Country Analysis Briefs*. Energy Information Administration [online] n.d. [cited: June 30, 2010] (http://www.eia.doe.gov/cabs/index.html).

16. Williams N: **New focus on tar sands**. *Curr Biol* 2010, **20**:R461-R462.

17. Kontorovich AE, Epov MI, Burshtein LM, Kaminskii VD, Kurchikov AR, Malyshev NA, Prischepa OM, Safronov AF, Stupakova AV, Suprunenko OI: **Geology and hydrocarbon resources of the continental shelf in Russian Arctic seas and the prospects of their development**. *Russ Geol Geophys* 2010, **51**:1.

18. EIA: *Summary: U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Proved Reserves 2009*. Washington, DC, USA: Energy Information Administration; 2010.

19. Kavanagh RJ, Burnison BK, Frank RA, Solomon KR, van der Kraak G: **Detecting oil sands process-affected waters in the Alberta oil sands region using synchronous fluorescence spectroscopy**. *Chemosphere* 2009, **76**:120-126.

20. Sudiro M, Bertucco A: **Production of synthetic gasoline and diesel fuel by alternative processes using natural gas and coal: process simulation and optimization**. *Energy* 2009, **34**:2206-2214.

21. Van Vliet OPR, Faaij APC, Turkenburg WC: **Fischer–Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis**. *Energy Convers Manage* 2009, **50**:855-876.

22. Hu X, Chang S, Lia J, Qin Y: **Energy for sustainable road transportation in China: Challenges, initiatives and policy implications**. *Energy* 2010, **35**:4289-4301.

23. Elcock D, Gasper J, Moses DO: *Environmental Regulatory Drivers for Coal Bed Methane*. s.l.: Argonne National Laboratory; 2002:. W-31-109-ENG-38.

24. • Adams WM, Jeanrenaud SJ: **Transition to sustainability: towards a humane and diverse world**. *IUCN Future of Sustainability Initiative 2008*. Gland, Switzerland: International Union for Conservation and Nature; 2008. . ISBN: 978-2-8317-1072-3.

Adams and Jeanrenaud's *Transition to Sustainability: Towards a Humane and Diverse World* is an all encompassing review of the major environmental challenges that we face today and how each challenge is interdependent. Although quite hopeful and wildly optimistic for the environmental movement, it still provides inspiring goals in ''energizing the future''.

25. OECD/IEA: *Energy Technology Perspectives 2008 — Scenarios and Strategies to 2050*. s.l.: Organization for Economic Cooperation and Development — International Energy Agency; 2008:. ISBN: 978-92-64-04142-4.

26. ADORE-IT: *Biofuels, from Dream to Mainstream. Adolescence for Renewable Energies in Transport* [online] n.d. [cited: May 4, 2011] (http://www.adore-it.eu/index.php?option=com_content&view=article&id=200%3A80-biofuels-possible-by-2050&catid=3%3Anews&Itemid=7&lang=en).

27. Verbruggen A, Al Marchohi M: **Views on peak oil and its relation to climate change policy**. *Energy Policy* 2010, **38**:5572-5581.

28. Gagnon N, Hall CAS, Brinker L: **A preliminary investigation of energy return on energy investment for global oil and gas production**. *Energies* 2009, **2**:490-503.

29. WNA: *Nuclear Power in Canada Appendix 2: Alberta*. World Nuclear Association [online] February 2010 [cited: June 24, 2010] (http://www.world-nuclear.org/info/inf49a_Alberta_Tar_Sands.html).

30. Addison K: **Is ethanol energy efficient?** *Journey to Forever* [online] n.d. [cited: June 24, 2010] (http://journeytoforever.org/ethanol_energy.html).

31. Webb S: **Europe crisis, China fiscal policy risks for oil**. *Reuters* [online] May 9, 2010 [cited: June 29, 2010] (http://www.reuters.com/article/idUSTRE6482BU20100509).

32. De Castro C, Miguel LJ, Mediavilla M: **The role of non conventional oil in the attenuation of peak oil**. *Energy Policy* 2009, **37**:1825-1833.

33. Exxon-Mobil: **Crude oil supply**. *Gasoline: A Global Market to Meet Your Needs* [online] n.d. [cited: June 28, 2010] (http://www.exxonmobil.com/corporate/newsroom/publications/c_gas_prices/c_crudeoil_ix.html).

34. Hubbert MK: *Nuclear Energy and the Fossil Fuels* [online] March 7–9, 1956 [cited: June 29, 2010] (http://www.hubbertpeak.com/hubbert/1956/1956.pdf).

35. Deffeyes K: *Beyond Oil — The View from Hubbert's Peak*. s.l.: Hill and Wang; 2005.

36. Salameh MG: **Oil crises, historical perspective**. *Encyclopedia Energy* 2004, **4**:633-648.

37. Mattson K: *What the Heck Are You up to, Mr. President?* New York: Bloomsbury; 2009:. ISBN: 1-59691-521-8.

38. •• Laherrère JH: *The Hubbert Curve: Its Strengths and Weaknesses* [online] n.d. [cited: June 28, 2010] Version proposed to Oil and Gas Journal on Feb 18 2000 (http://dieoff.org/page191.htm).

Jean Laherrère's *The Hubbert Curve: Its strengths and weaknesses* is an excellent introduction to Hubbert's analysis techniques.

39. Maugeri L: **Oil: never cry wolf — why the petroleum age is far from over**. *Science* 2004, **304**:1114-1115.

Maugeri's *Oil: never cry wolf — Why the petroleum age is far from over* was one of the few papers that attempted to show the flaws in the peak oil argument. The rebuttal from Meng and Bentley (41), although several years after Maugeri's original paper, is a well-written defense of peak oil.

40. Meng QY, Bentley RW: **Global oil peaking: responding to the case for 'abundant supplies of oil'**. *Energy* 2008, **33**:1179-1184.

41. Höök M, Hirsch R, Aleklett K: **Giant oil field decline rates and their influence on world oil production**. *Energy Policy* 2009, **37**:2262-2272.

42. •• Sorrell S, Speirs J, Bentley R, Brandt A, Miller R: *Global Oil Depletion — An Assessment of the Evidence for a Near-term Peak in Global Oil Production*. s.l.: UK Energy Research Council; 2009:. Available from http://www.ukerc.ac.uk/support/Global%20Oil%20Depletion (ISBN: 1-903144r-r0-35).

Global Oil Depletion — An assessment of the evidence for a near-term peak in global oil production from the UKERC (Steve Sorrell, Jamie Speirs, Rodger Bentley, Ada Brandt, and Richard Miller) is probably the best summary of the peak oil debate that has been written to date.

43. CERA: *Peak Oil Theory — ''World Running Out of Oil Soon'' — Is Faulty; Could Distort Policy & Energy Debate*. Cambridge Energy Research Associates [online] November 12, 2006 [cited: June 29, 2010] (http://www.cera.com/aspx/cda/public1/news/pressReleases/pressReleaseDetails.aspx?CID=8444)

44. Kontorovich AE: **Estimate of global oil resource and the forecast for global oil production in the 21st century**. *Russ Geol Geophys* 2009, **50**:237-242.

45. UN: *Joint Oil Data Initiative (JODI): Project on Monthly Oil Statistics*. United Nations Statistics Division [online] 2010 [cited: June 26, 2010] (http://unstats.un.org/unsd/energy/jodi.htm).

46. Jackson P: *Why the "Peak Oil" Theory Falls Down — Myths, Legends and the Future of Oil Resources*. Cambridge, MA, USA: CERA Advisory Services; 2006:. [Decision Brief].

47. Klare MT: *Rising Powers, Shrinking Planet: The New Geopolitics of Energy*. s.l.: Holt Paperbacks; 2009:. ISBN: 0-805-08921-7.

48. Knight H: **Wonderfuel gas**. *New Sci* 2010, **206**:44-47.

49. Lynch MC: **The new pessimism about petroleum resources: debunking the Hubbert Model (and Hubbert Modelers)**. *Miner Energy* 2003, **18**:21-32.

50. Sorrell S, Speirs J: **Hubbert's legacy: a review of curve-fitting methods to estimate ultimately recoverable resources**. *Nat Resour Res* 2010, **19**:209-230.

51. IEA: *Energy Security*. International Energy Agency [online] 2010 [cited: 12 27, 2010] (http://www.iea.org/subjectqueries/keyresult.asp?KEYWORD_ID=4103).

52. APERC: *A Quest for Energy Security in the 21st Century*. Tokyo: Institute of Energy Economics, Asia Pacific Energy Research Centre; 2007 . ISBN: 978-4-931482-35-7 In: *www.ieej.or.jp/aperc*.

53. Hughes L, Shupe D: **Applying the four 'A's of energy security as criteria in an energy security ranking method**. In *Routledge Handbook of Energy Security.* Edited by Sovacool B. s.l.: Routledge; 2010.

54. Hofmeister J: *Why We Hate the Oil Companies: Straight Talk from an Energy Insider*. s.l.: Palgrave Macmillan; 2010:. ISBN: 0-230-10208-5.

55. Korowicz D: *Tipping Point: Near-Term Systemic Implications of a Peak in Global Oil Production — An Outline Review*. FEASTA.org [online] March 15, 2010 [cited: April 16, 2011] (http://www.feasta.org/2010/03/15/tipping-point-near-term-systemic-implications-of-a-peak-in-global-oil-production-an-outline-review/).

56. Hirsch R: **Mitigation of maximum world oil production: shortage scenarios**. *Energy Policy* 2008, **36**:881-889.
Robert Hirsch's analysis of how oil shortages can be handled, *Mitigation of maximum world oil production: Shortage scenarios*, is a good overview of how the problem may have to be handled should it arise.

57. IEA: *Oil Markets and Emergency Preparedness*. International Energy Agency [online] n.d. [cited: June 28, 2010] (http://www.iea.org/about/ome.htm).

58. Campbell C: *The Oil Depletion Protocol* [online] n.d. [cited: June 29, 2010] (http://www.oildepletionprotocol.org/).

59. Maconachie R, Tanko A, Zakariy M: **Descending the energy ladder? Oil price shocks and domestic fuel choices in Kano, Nigeria**. *Land Use Policy* 2009, **26**:1090-1099.

60. Hughes L: **The four 'R's of energy security**. *Energy Policy* 2009, **37**:2459-2461.

61. Bilgin M: **Geopolitics of European natural gas demand: Supplies from Russia, Caspian and the Middle East**. *Energy Policy* 2009, **37**:4482-4492.

62. Goldthau A: **Rhetoric versus reality: Russian threats to European energy supply**. *Energy Policy* 2008, **36**:686-692.

63. Shealy M, Dorian JP: **Growing Chinese coal use: dramatic resource and environmental implications**. *Energy Policy* 2010, **38**:2116-2122.

64. EIA: *Annual Energy Outlook*. Washington: Energy Information Administration; 2010:. DOE/EIA-0383(2010).

65. Biello D: *Waste Not, Want Not: Energy via the Smart Grid*. ScientificAmerican.com [online] February 9, 2009 [cited: June 22, 2010] (http://www.scientificamerican.com/podcast/episode.cfm?id=6BCDB36C-A91E-8688-8CCA29A380672B65).

66. Hughes L: **Meeting residential space heating demand with wind-generated electricity**. *Renew Energy* 2010, **35**:1765-1772.

67. Bradshaw M: **Global energy dilemmas: a geographical perspective**. *Geograph J* 2010, **176**:275-290.

68. Curtis F: **Peak globalization: climate change, oil depletion and global trade**. *Ecol Econ* 2009, **69**:427-434.

69. Bentley R, Boyle G: **Global oil production: forecasts and methodologies**. *Environ Plann B Plann Des* 2008, **4**:609-626.

70. EIA: *International Energy Outlook — 2010*. Washington: Energy Information Administration; 2010:. DOE/EIA-0484(2010).

71. Exxon-Mobil: *Global Liquids Supply Grows*. Exxon-Mobil [online] n.d. [cited: June 30, 2010] (http://www.exxonmobil.com/Corporate/energy_o_sup_liquid.aspx).

72. OPEC: *World Oil Outlook*. Vienna, Austria: Organization of Petroleum Exporting Countries; 2010:. ISBN: 978-3-9502722-1-5.

73. Exxon-Mobil: *2010 Summary Annual Report*. Exxon-Mobil Annual Reports [online] April 2011 [cited: May 2, 2011] (http://www.exxonmobil.com/Corporate/Files/news_pubs_sar_2010.pdf).