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Energy 29 (2004) 1673–1696
ENERGY
www.elsevier.com/locate/energy

Forecasting the limits to the availability and diversity of global conventional oil supply

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Received 31 July 2003

Abstract

Due to the critical importance of oil to modern economic activity, and oil's non-renewable nature, it is extremely important to try to estimate possible trajectories of future oil production while accounting for uncertainties in resource estimates and demand growth, and other factors that might limit production. In this study, we develop several alternate future scenarios for conventional oil supply, given the current range of the estimates of resource availability and of future demand, and assuming that production will continue to increase unconstrained by political or economic factors such as deliberate withholdings or prolonged global recession. Our results predict that global production of conventional oil will almost certainly begin an irreversible decline somewhere between 2004 and 2037, at 22 to 42 billion barrels per year, depending upon how much oil is available from the earth's crust and the growth rate in its use. In addition, we found that the increasing domestic use of conventional oil in oil-producing countries is very likely to eliminate over time the ability of these countries to export oil to net-consumer countries, so that the number of net-exporting countries will be reduced from 35 today to between 12 and 28 by 2030, and fewer subsequently. The geopolitical and economic implications of these trends are likely to be pronounced if reliance on cheap oil is not reduced prior to the peak.

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0360-5442/$ - see front matter
doi:10.1016/j.energy.2004.04.043

1. Introduction

Conventional oil is one of the critical natural resources of the modern world, supplying approximately 40% of global energy in 2000 as well as extremely important and inexpensive lubricants and chemical feedstocks [1]. Its use is linked closely to the wealth of the industrialized nations as well as the dramatic economic expansion of developing economies, many of which have few energy resources of their own besides biomass and direct solar energy [2,3]. Nearly all projections of future global energy use assume a substantial increase in the demand for oil products in coming decades because of continued high levels of consumption in developed countries and projected increases in developing countries, despite any likely conservation measures or gains in energy efficiency [4]. Additionally, in the near term, large quantities of oil will probably be used to satisfy increasing demands for other resources such as freshwater from desalination that will be required by the rapidly growing human population of the Middle East and elsewhere [5–7]. Oil is essentially a non-renewable resource. While the current sources of exported oil are geographically diverse, most of the remaining oil reserves are highly concentrated in countries located in the Middle East, within the Former Soviet Union (FSU), and, to a lesser degree, in North and West Africa. This makes oil even more of a geopolitical issue in the future than it is now. Given that oil consumption is increasing more rapidly in most oil-exporting nations than the world as a whole, it is probable that in the near future many countries that currently export oil will no longer be able to do so.

Given the substantial uncertainties associated with forecasting oil production, one can ignore the question of the availability of future oil supplies, consult the oracle of Delphi or its equivalent, or, as we do here, attempt to identify the range of future supply scenarios by applying such science as we can bring to bear on the problem. Subsequently, the likely additional influence of the less tractable issues can be considered. In this study, we develop several alternate future scenarios for conventional oil supply. Our objective is to develop a forecast that will be useful for public policy making. We realize that any forecasting is an imperfect endeavor, but consider it preferable to the neglect that dominates this issue in current energy policy-making circles.

Several scientific approaches have been used in the past to predict future patterns of oil production. Geological models emphasize the size and quality of resource stocks, but tend to ignore the economic reality that the real price of oil affects both recoverable supply and rate of recovery. Supply constraints clearly have raised oil prices in the past, provoking responses that include increased investment in additional exploration and production. These models use mathematical formulations to represent the observed pattern of accelerated production followed by a peak (or several peaks) when about half of the original resource has been extracted, and subsequently a progressive, probably exponential decline [8–13]. This kind of analysis was pioneered by Marion King Hubbert [8], who in 1956 predicted accurately that oil production in the lower 48 states of the US would peak by 1970.

Hubbert's basic model remains very attractive to many (but not all) oil analysts, and in the past decade a number of "neo-Hubbertarians" have made predictions of the timing of peak production that vary from about 2002 to 2030. The majority of these studies assumed an ultimately recoverable volume (often termed extractable ultimate resource or EUR) for the world of roughly two trillion barrels of oil (TBO) [9–14]. Some of these studies assessed production at the world level only, while others made predictions for the world based on country-level analysis. Some members of the Association for Study of Peak Oil (ASPO) recently forecasted production at the country and world level assuming country-level EUR estimates totaling approximately two trillion barrels, but did not evaluate sensitivity to a variation in either EUR estimates or future demand trends [12]. Using the Uppsala–Campbell model, they predicted that world oil production had already peaked in 2000, and will remain at approximately its current level of 22 billion barrels of oil per year (BBO $year^{-1}$) until 2010, when the depletion midpoint will bring an unavoidable decline in production (Table 1, Figs. 9 and 10). Edwards [14] assessed world production using 2.84 TBO for world EUR. His model increased production 1.4% annually until it peaked in 2020 at 33 BBO $year^{-1}$. Bartlett [9] fitted gaussian curves to production data under scenarios of two, three and four trillion barrels for world EUR to generate predictions of peak dates from 2004 to 2030 at from 26.5 to 39.5 BBO $year^{-1}$ (Table 1, Figs. 9 and 10). He did not assess the impact of alternate demand trends, however.

A study by the Energy Information Administration (EIA) [13] of the US Department of Energy, in contrast to Hubbert's methods, assumed world oil production would increase until the reserves to production ratio (R/P) fell to a value of 10. This assumption effectively resulted in a peak when approximately 70–80% of the EUR had been depleted, a pattern which does not appear consistent with the actual patterns of post-peak nations such as the United States,

Table 1
Results of other recent world conventional oil production forecasts. Resource levels are in trillion barrels of oil (TBO). Production rates are in billions of barrels of oil per year (BBO $year^{-1}$). Percents given for different scenarios are the annual rate of increase in production prior to peak

Author	Scenario		Year of peak or decline-point	Production at decline-point (BBO $year^{-1}$)
	World EUR (TBO)	Annual production growth (%)		
Aleklett and Campbell [12]	1.9	0.0	2010	22.0
Bartlett [9]	2.0	Varies	2004	26.5
	3.0	Varies	2019	33.0
	4.0	Varies	2030	39.5
Cavallo [11][a]	2.3	2.0	2015–2020	NA
Edwards [14]	2.84	1.4	2020	33
EIA [13]	2.25	1.0	2033	34.8
	2.25	2.0	2026	42.8
	2.25	3.0	2021	48.5
	3.0	1.0	2050	41.2
	3.0	2.0	2037	53.2
	3.0	3.0	2030	63.3
	3.9	1.0	2067	48.8
	3.9	2.0	2047	64.9
	3.9	3.0	2037	77.8

Source: Studies in author column.
[a] This study forecasted the peak of non-OPEC production only.

Romania and others [15]. EIA used the range of probabilistic estimates of world oil reserves developed by the United States Geological Survey (USGS) [16] to test the impact of varying production growth rates on future production paths at the global level. Forecasts of peak oil production from EIA's study ranged from 2021 to 2067 at from 34.8 to 77.8 BBO year^{-1} (Table 1, Figs. 9 and 10). The EIA analysis did not include other current resource estimates that are typically considerably lower than USGS's, however [12]. Cavallo [11] analyzed non-OPEC conventional oil production at the country level using the mean USGS reserve estimates, but excluded reserve growth and very inaccessible oil. His model increased production by 2% annually until the decline point occurred at R/P between 10 and 15. He predicted a non-OPEC production peak from 2015 to 2020 (Table 1, Figs. 9 and 10), followed by a peak in world conventional oil production soon afterwards.

In general, the above predictions of the timing of the peak in world production of conventional oil have shown sensitivity to assumptions about the "behavior", or shape, of the production curve over time, and especially (EUR). None of the above studies or methods examined explicitly the potential impact of other factors on oil production, such as constraints on the maximum annual growth rate of production imposed by physical, technological or socio-economic factors, or the influence of domestic consumption on the export capability of oil-producing nations.

Economic models, in contrast, are based on the relation between prices and production, but they essentially ignore critical geological attributes of oil stocks [17]. Some economists have argued that future patterns of petroleum discovery and production will be affected more by prices than by geology, suggesting that price increases from petroleum scarcity will spur increased exploration and production resulting in more oil coming to the market [18,19]. While there may be merit to such analyses, it is important to note that the relation between price and supply is far from perfect, and previous economic forecasts have mostly overestimated production levels [17,20]. When oil prices increased greatly during 1970–1981, and remained high until the steep decline at the end of 1985, the resultant increased drilling effort in the early 1980s found less additional oil in the US compared to less intensive efforts of the 1960s and 1970s. This increased effort also greatly reduced the economic and energy efficiency of finding that oil, although a full analysis of that issue is more complex [20,21]. During 1970–1985, oil production in the US fell by about 20% [21]. In our view, increased price usually implies increased requirements for energy investments for poorer quality or less accessible resources, and hence declines in energy return on investment. Eventually, the finite nature of the resource precludes investment.

Any comprehensive analysis of the future supply and geography of global oil production should, in addition to conducting a comprehensive evaluation of sensitivity to uncertainty in resource estimates and demand growth rates, analyze future production and consumption patterns at the country level, and disaggregate exporters and importers. This will foster a better understanding of the future diversity and geography of oil supplies for the 180 net-oil-importing nations. Such an analysis should also evaluate the impact of other factors that influence oil production, such as possible physical or economic constraints on increasing production, and the proportion of EUR produced at the time at which the peak or decline point may occur.

2. Methods

We developed a series of possible trajectories for conventional oil production rates and exports at both the national (47 major oil-producing countries) and the global scale for the period 2002–2060 based on recent production and consumption data, a range of estimates of EUR, the most recent high and low estimates of the rates of growth in oil demand, variation in the proportion of EUR extracted at the decline point, and potential limits to the abilities of nations to increase annual production. The nations we evaluated accounted for approximately 99% of the 2000 global production of conventional oil [22].

A number of caveats are in order, given the large range in existing estimates of EUR and future production and the large political implications of the results. Our analysis pertains only to the ''conventional'' part of the global oil resource. Conventional oil refers to all oil produced from reservoirs through a well bore using any primary, secondary, improved, enhanced or tertiary methods. Conventional oil is generally not considered to include heavy oil, oil shale, tar sands, or natural gas liquids, the production of which typically involves mining or additional processing of the oil in place. It is this conventional oil that is ''cheap'' to extract and use, and that has contributed to the historical importance of petroleum on a global scale. The Canadian Association of Petroleum Producers decided in 2002 to classify oil from Canadian tar sands as conventional [23], causing a large jump in conventional oil reserve estimates. We do not think this reclassification is warranted.

While the world does contain large amounts of unconventional oil resources that can substitute for crude oil, the substantially higher capital and production costs, requirements for natural gas for upgrading and the environmental impacts associated with extracting these resources make their potential contribution to the world's energy mix unclear [24]. Production of most non-conventional liquids will likely not increase substantially until conventional oil production peaks, and it is too soon to tell how non-conventional production will develop over time. The global availability of large coal deposits and a less well-understood supply of natural gas (including highly speculative estimates about gas hydrates) does suggest that there will probably not be a shortage of other fossil energy sources in the near to mid-term for many countries [4].

A few comments should also be made on our use of the total volume of recoverable oil orignally present (EUR) in our models and its relation to other reserve types. EUR equals the total of known and probable reserves. ''Proved'' reserves have a very high probability of being extracted, and are typically much smaller than what is eventually recovered from a field. ''Known'' reserves include proved reserves plus oil already extracted (i.e. cumulative production). ''Probable'' reserves include estimates of undiscovered oil that are likely to be found. By using EUR, we assume that all categories of reserves will become proved and economically recoverable at some point. This amounts to assuming that the stimulatory effects of rising price on discovery and development are instantaneous and price does not retard demand significantly. Past forecasts that used only proved reserves, which underestimate the amount of oil ultimately recovered, were doomed to predict too-early supply shortages. We used EUR in an attempt to avoid this same mistake.

Our forecasts should not be considered explicit predictions, but rather estimates of rates of production and export potential over time given the various estimates of resource size and demand growth. They explicitly do not include social and economic factors such as restrictions on production for political reasons or to drive up prices. However, the range of demand growth rates used will probably encompass the effects of these factors. Since past trends include in them the ongoing effects of previous technological innovation, changes in consumer behavior and environmental regulation, our forecasts implicitly assume similar rates of change for the future. Changes in any of these factors could cause actual production to deviate substantially from our individual forecasts, although probably not beyond the boundary generated by our sensitivity analysis using various estimates of EUR and other factors.

2.1. Forecasting approach

We developed scenarios based on three different country-specific estimates of EUR: low, medium and high, that sum to a global total of 1.9, 2.9 and 4.0 trillion barrels of recoverable oil (TBO), respectively. These estimates of the EUR represent the range found in the literature from the lowest estimates of the neo-Hubbertarians (which is somewhat lower than the USGS's 95% confidence value of 2.3 TBO) to the mean value of USGS to their 5% confidence value. These were combined with two scenarios of economic growth (low and high) to yield six separate principal forecasts. In addition, we re-evaluated each of these six combinations assuming three maximum rates of increase in oil production (5.0%, 7.5%, and 15.0% per year). These 18 scenarios were in turn re-evaluated twice—once assuming production peak/decline point occurred when 50% of EUR had been extracted, and once when 60% had been extracted. In six additional scenarios, we assumed no growth in oil demand.

We required the following data for each country (in million of barrels or millions of barrels per year): (1) the domestic consumption of oil in 2001, (2) the projected growth rates of oil consumption, (3) the volume of oil originally present before any extraction (EUR), (4) the annual production for 2001, (5) the cumulative production to date (end of 2001), and (6) estimates of oil remaining in 2001 (which is 3 minus 5 above).

Historical oil consumption, production and projected annual increase rates for oil demand were obtained for each country from the United States Department of Energy, Energy Information Administration (EIA). The specific source for production was the International Energy Annual 2001 Table G2 [25]. The source for consumption was the International Energy Annual 2001 Table 1.2 [26]. Consumption increase rates were obtained from USDOE—International Energy Outlook 2002, Tables, B4 and C4 [27].

Medium and high estimates of EUR were derived from the mean and 5% probability estimates of the United States Geological Survey's 2000 assessment of world petroleum resources [16], and low estimates of EUR were from the Uppsala–Campbell model [12]. The low estimates sum to a world value that is 200–300 BBO (about 10%) less than USGS's 95% probability estimate. The main reasons for these differences among the estimates are that Uppsala–Campbell data do not include polar and deep water resources and the USGS assumes a rather liberal "reserves growth" factor (for the first time in their assessments) intended to account for significant increases in the proportion of a field that is recoverable due to new technology. We used Uppsala–Campbell data for our lower estimates, but chose to include oil from Alaska as conventional given the well-established nature of Alaskan oil operations. By using USGS EUR data in some scenarios, we implicitly assume in those cases that conventional production will eventually draw from deep-water and polar regions as it increases over time.

Which of these conventional oil inclusions or exclusions are appropriate is a contentious matter amongst oil investigators. We assume the published EUR estimates (USGS and otherwise) to already include the manifestation of possible future advances in recovery rates. We have not ourselves assessed the technological feasibility or likelihood of achieving any average level of world reserves growth over time.

We had to correct for the fact that natural gas liquids and unconventional oil were included in publicly available production and consumption databases, but not in estimates of EURs or in the Uppsala–Campbell data. We multiplied historical demand and production data by the country-specific ratio (world average was 0.84174) 2000 production data from Uppsala–Campbell (with Alaskan oil added) to the 2000 total petroleum liquids production data available from EIA [25] to correct for this. Because our analysis begins in 2001, it was also necessary to update EIA's year 2000 country-specific demand data. While 2001 country-specific demand data were not available in time for this writing, world-level 2001 demand data were available, which were 0.99978 of 2000 demand. We multiplied 2000 country-specific demand data by this factor to obtain 2001 data for each nation.

We made our forecasts using depletion extrapolation techniques modified from Campbell [8–30], which we describe below. A more detailed description of the logic and formulas used to determine demand and production in a nation for any year is available from the authors upon request.

In our principal set of forecasts (three EUR levels by two demand increase levels), we assume that pre-peak production increases annually in each country to meet domestic demand, plus an increment to help meet the increasing net world demand. We capped the increase in annual production at a certain percentage, depending on the scenario. We chose 7.5% as the "base" for comparison after reviewing the range of actual rates of increase seen in a number of countries in the past 20 years. We forced annual production in each country to increase until cumulative production equaled 50% of EUR, at which time production reached the decline point/peak. This is based on Hubbert's assumption that the rate of non-renewable resource exploitation will rise to a peak occurring when approximately 50% of the resource has been extracted. Annual production of anthracite coal from Pennsylvania (1830–1980) followed this trend (see e.g. Deffeyes [31]). An analysis by Duncan [15] found that of the over 50 oil-producing nations whose production has peaked, the peak occurred in the vast majority of cases when 40–60% of EUR had been extracted. Our own assessment of 21 nations whose peak occurred after 1978 found that 16 nations peaked when from 40% to 60% of EUR (using Uppsala–Campbell data [12]) was extracted, four nations peaked when more than 60% had been extracted and one nation peaked when less than 40% had been extracted. It should be noted that in some cases our forecasted peak is only a peak relative to the start of model (2001). Our forecasts generate the point of irreversible decline, which is not always the peak of record.

We reduced production each year subsequent to the peak by the "decline rate" (see below) regardless of projected demand. The decline rate is the proportion of remaining oil that is produced in a given year [29], and results in a country-specific exponential decline. As domestic use exceeds domestic production, each exporting country modeled ceases to be a supplier, and instead imports any oil needed to meet the shortfall from the remaining exporters. Each remaining pre-peak country then increases production each year accordingly until its cumulative production reaches 50% of its own EUR. As production in more nations peaks over time, remaining producers must increase production at higher rates (if possible) if world demand is still to be met.

We also assessed the sensitivity of production trajectories to changes in the maximum possible annual increase in production by adding scenarios assuming maximum rates of 5.0% and 15.0% to our basic assumption of 7.5%. Even so, there are currently two to three countries with substantial excess oil production capacity. The ability of these countries to increase production quickly, without major new discoveries or investment, will last only as long as their excess capacity. Because of the possibility that the production from some fields within a country may not peak when 50% of EUR has been extracted, we ran additional scenarios assuming a peak at 60% of EUR extracted.

Based on the historical experience of post-peak nations such as the US, we smoothed the tops of the production curves for each country rather than allowing them to peak abruptly. We damped the rate of increase or decrease in production when cumulative production was between 45% and 55% of EUR by multiplying the rate by a factor that decreased from 0.37 to 0.30 as the absolute value of the difference between 50% of EUR and cumulative production increased (e.g., a dampening factor at 49% EUR was the same as that at 51%). Smoothing the country-specific production curves caused them to peak one or two years later and at slightly lower production volumes and world production and demand to diverge one or two years earlier than they would have without smoothing.

All calculations were performed using Microsoft® Excel 2000 spreadsheet software. The explicit addition of price and geo-political influences, factors that are highly uncertain and difficult to model, would be a good complement to our approach.

3. Results

Our principal results are that if past oil consumption patterns are continued and if the EUR volumes actually realized are within our most probable range of estimates, global production of conventional oil will most likely reach a peak or decline point between 2004 and 2037 at between 24 and 42 BBO year^{-1}. Our high reserves scenarios, that assume USGS's 5% probability estimates for EUR, forecast the peak of global oil production to occur as late as 2053 at 54 BBO year^{-1} (Table 2, Figs. 1–6). Due to the combination of peak smoothing and limits on the annual rate of production increase at the national level, global production of conventional oil in our model is unable to match forecasted global demand increases at some point prior to peaking, causing a divergence of the two after about 2001–2031, or 2052 if the highest EUR scenarios are included (Table 2, Figs. 1–6). Even if we assume no growth in demand, irreversible production decline is reached starting from 2014 to 2061 depending on estimates of EUR values (Table 2). As the domestic use of oil by individual producer nations continues to increase, it will decrease and eventually eliminate their role as exporters (Figs. 7 and 8). Over time more and more oil exporters will become net importers, and oil production will become increasingly concentrated in a very few countries in the Middle East, the Former Soviet Union and Africa (Fig. 8). The timing of this concentration will tend to coincide with the peak in global oil production. The number of exporting countries will decrease from the current 35 today to between 12 and 28 in 2030 (Table 2). If realized EUR levels are close to our low-EUR estimate, then there will be between 0 and 7 exporting countries left by 2050.

Table 2
Forecasts of conventional oil production for the period 2002–2060, using 2001 as starting year. The 36 scenarios were defined by varying oil resource estimates (EUR—3 levels), demand growth rates (2 levels), limits on future annual production growth rates (3 levels), and percent of EUR extracted at which peak occurs (2 levels). The six "zero" growth scenarios are defined by 3 EUR levels, and percent of EUR extracted at which peak occurs. Resource levels are in trillion barrels of oil (TBO). Production rates are in billions of barrels of oil per year (BBO $year^{-1}$). Net producers are those countries for which oil production exceeds internal demand

Scenario				World EUR (TBO)	# Net producer nations by year					Year of global decline	Year global demand unmet	Production at decline-point (BBO $year^{-1}$)
EUR level	Demand growth	% EUR at decline	Maximum production growth $year^{-1}$(%)		2010	2020	2030	2040	2050			
Low	Low	50	5.0	1.9	29	22	15	14	7	2004	2001	22
Low	High	50	5.0	1.9	28	17	14	5	3	2004	2001	22
Mid	Low	50	5.0	2.9	30	26	24	21	16	2029	2020	32
Mid	High	50	5.0	2.9	28	25	20	13	9	2027	2001	35
High	Low	50	5.0	4.0	34	28	27	24	23	2043	2033	41
High	High	50	5.0	4.0	31	28	25	21	13	2034	2013	51
Low	Low	50	7.5	1.9	29	21	15	14	7	2013	2001	24
Low	High	50	7.5	1.9	28	16	14	5	2	2013	2001	24
Mid	Low	50	7.5	2.9	30	26	24	21	16	2029	2020	35
Mid	High	50	7.5	2.9	28	25	20	13	8	2024	2016	43
High	Low	50	7.5	4.0	34	28	26	24	23	2043	2033	44
High	High	50	7.5	4.0	32	28	25	21	13	2033	2027	60
Low	Low	50	15.0	1.9	29	21	15	14	7	2011	2011	27
Low	High	50	15.0	1.9	29	16	14	4	0	2014	2010	32
Mid	Low	50	15.0	2.9	30	26	24	22	16	2031	2030	36
Mid	High	50	15.0	2.9	30	25	20	13	8	2025	2024	49
High	Low	50	15.0	4.0	34	28	26	24	23	2046	2040	46
High	High	50	15.0	4.0	32	26	25	21	13	2034	2027	69
Low	Low	60	5.0	1.9	30	22	15	11	6	2009	2009	25
Low	High	60	5.0	1.9	29	16	14	5	2	2008	2001	25
Mid	Low	60	5.0	2.9	30	27	24	20	14	2032	2027	36
Mid	High	60	5.0	2.9	30	25	20	14	8	2029	2010	42
High	Low	60	5.0	4.0	35	30	28	24	24	2046	2041	46
High	High	60	5.0	4.0	34	28	25	21	14	2037	2016	56
Low	Low	60	7.5	1.9	30	22	15	11	6	2019	2010	26
Low	High	60	7.5	1.9	29	17	13	5	0	2018	2001	29
Mid	Low	60	7.5	2.9	30	27	24	20	14	2037	2032	39

(continued on next page)

Table 2 (*continued*)

Scenario				World EUR (TBO)	# Net producer nations by year					Year of global decline	Year global demand unmet	Production at decline-point (BBO $year^{-1}$)
EUR level	Demand growth	% EUR at decline	Maximum production growth $year^{-1}$(%)		2010	2020	2030	2040	2050			
Mid	High	60	7.5	2.9	30	25	20	13	8	2028	2024	50
High	Low	60	7.5	4.0	35	29	28	24	24	2051	2042	49
High	High	60	7.5	4.0	34	28	25	21	13	2036	2034	71
Low	Low	60	15.0	1.9	30	22	15	11	4	2018	2020	30
Low	High	60	15.0	1.9	29	17	12	2	0	2017	2017	39
Mid	Low	60	15.0	2.9	30	27	24	20	14	2037	2038	42
Mid	High	60	15.0	2.9	30	25	20	13	7	2031	2029	58
High	Low	60	15.0	4.0	35	29	28	24	24	2053	2052	54
High	High	60	15.0	4.0	34	28	25	21	13	2039	2032	83
Low	Zero	50	7.5	1.9	31	24	20	16	14	–	2014	23
Mid	Zero	50	7.5	2.9	32	28	27	24	21	–	2037	23
High	Zero	50	7.5	4.0	33	31	29	26	25	–	2056	23
Low	Zero	60	7.5	1.9	31	23	20	15	12	–	2021	23
Mid	Zero	60	7.5	2.9	32	29	27	23	20	–	2047	23
High	Zero	60	7.5	4.0	34	31	29	27	25	–	>2060	23

Source: Results of this study.

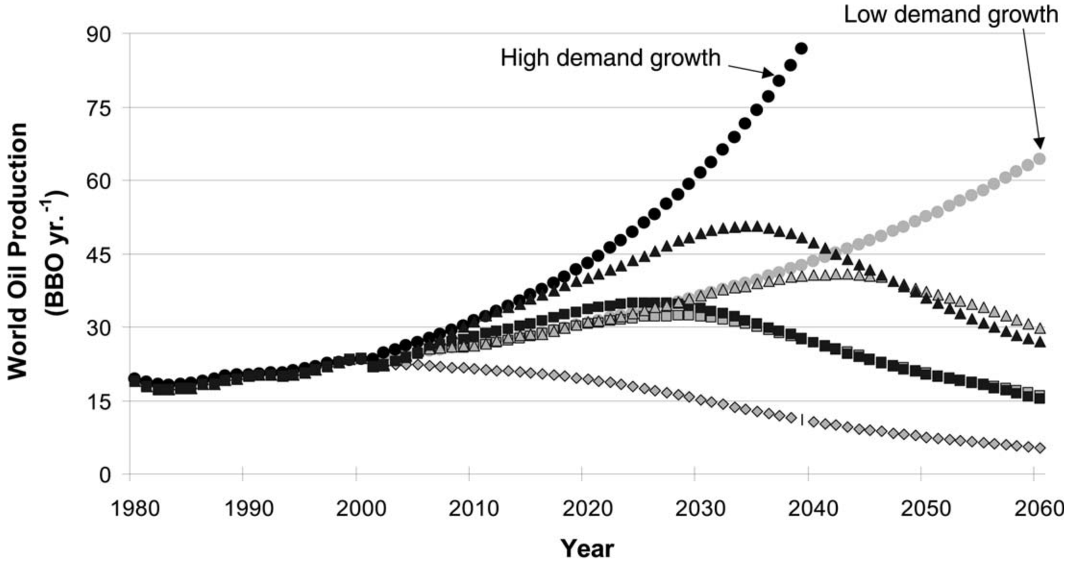

Fig. 1. Forecasted trajectories of world conventional oil production and demand for the period 2002–2060, assuming peak at 50% of EUR extracted and a 5.0% limit on annual growth. Values for 1980–2001 are derived from historical data. Trajectories are the same when assuming low EUR for both high and low demand growth in this case. ● Historical and forecasted demand assuming high growth. ● Historical and forecasted demand assuming low growth. ▲ World conventional oil production tracking high demand growth, assuming high EUR. △ World conventional oil production tracking low demand growth, assuming high EUR. ■ World conventional oil production tracking high demand growth, assuming medium EUR. □ World conventional oil production tracking low demand growth, assuming medium EUR. ◆ World conventional oil production tracking high demand growth, assuming low EUR. ◇ World conventional oil production tracking low demand growth, assuming low EUR.

4. Discussion

4.1. Comparison to other studies

Some of our results are similar to those of other recent analyses and some are not. Our estimates of the timing of peak production using lower EUR estimates are similar to those of other recent studies using similar EUR values (Tables 1 and 2, Figs. 9 and 10) [9,12]. This is not surprising, as constraining oil production to decline when 50% of two trillion barrels of oil has been extracted allows production to continue at even current levels for no more than a few years before the peak or decline point is reached. Larger differences are apparent when we compare our results to those of others using methods dissimilar to ours, especially for scenarios assuming EUR volumes of 3–4 trillion barrels (Tables 1 and 2, Figs. 9 and 10). EIA's assumption of a peak or decline-point when R/P declines to 10 (which occurs at roughly 70–80% exhaustion of EUR) differs greatly from our methods and leads to later and higher peaks relative to our results (Tables 1 and 2, Figs. 9 and 10) [13]. EIA also assumed a post-peak decline that maintains R/P equal to 10, resulting in steeper declines than caused by our methods [13]. EIA's use of R/P equals 10 to model the behavior of other nations is based on US experience, and has been questioned by some analysts [11]. Given that reported reserves in the US often

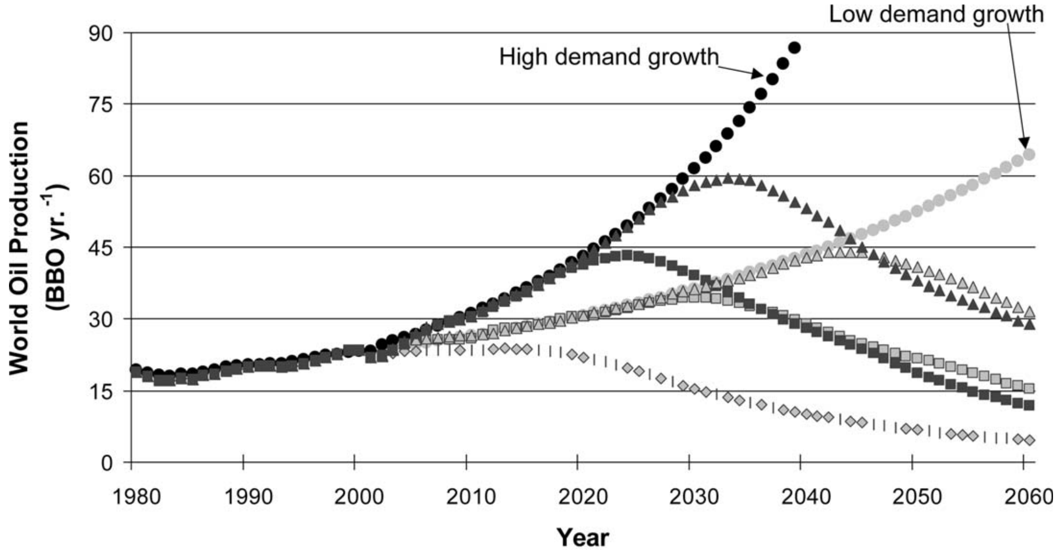

Fig. 2. Forecasted trajectories of world conventional oil production and demand for the period 2002–2060, assuming peak at 50% of EUR extracted and a 7.5% limit on annual growth. Values for 1980–2001 are derived from historical data. Trajectories are the same when assuming low EUR for both high and low demand growth in this case. ● Historical and forecasted demand assuming high growth. ● Historical and forecasted demand assuming low growth. ▲ World conventional oil production tracking high demand growth, assuming high EUR. △ World conventional oil production tracking low demand growth, assuming high EUR. ■World conventional oil production tracking high demand growth, assuming medium EUR. □ World conventional oil production tracking low demand growth, assuming medium EUR. ◆ World conventional oil production tracking high demand growth, assuming low EUR. ◇ World conventional oil production tracking low demand growth, assuming low EUR.

increase due to conservative original reporting, applying this same method to other nations with different reporting practices may not be warranted.

Bartlett's [9] gaussian curve-fitting produced estimates of peak timing similar to those of our scenarios when we assumed 7.5% annual growth limits, high demand growth rates and medium to high EURs, but his peak rates were 23–34% lower than ours and his curves, unlike ours, had symmetrical rising and falling sections (Tables 1 and 2, Figs. 1–6). These differences in peak productions and curve shapes are the result of large differences in methodology, as Bartlett assumed curves of perfect symmetry that minimized the root mean squared error between curve and historical data, while our world-level curves were the manifestation of country-level processes and were not generated by curve-fitting or constrained to be symmetrical.

4.2. Impact of input variation

The impact of changes in major model parameters on the timing and volume of peak oil production, and the number of net producers in any given year, was varied although generally rather obvious (Tables 2 and 3, Figs. 1–6). For any given EUR, scenarios in which production follows the higher demand growth path generated earlier and higher peaks than scenarios following the low demand growth path (Table 2, Figs. 1–6). Production paths for some low EUR scenarios are the same whether we assumed low or high demand growth (Figs. 1 and 2), because

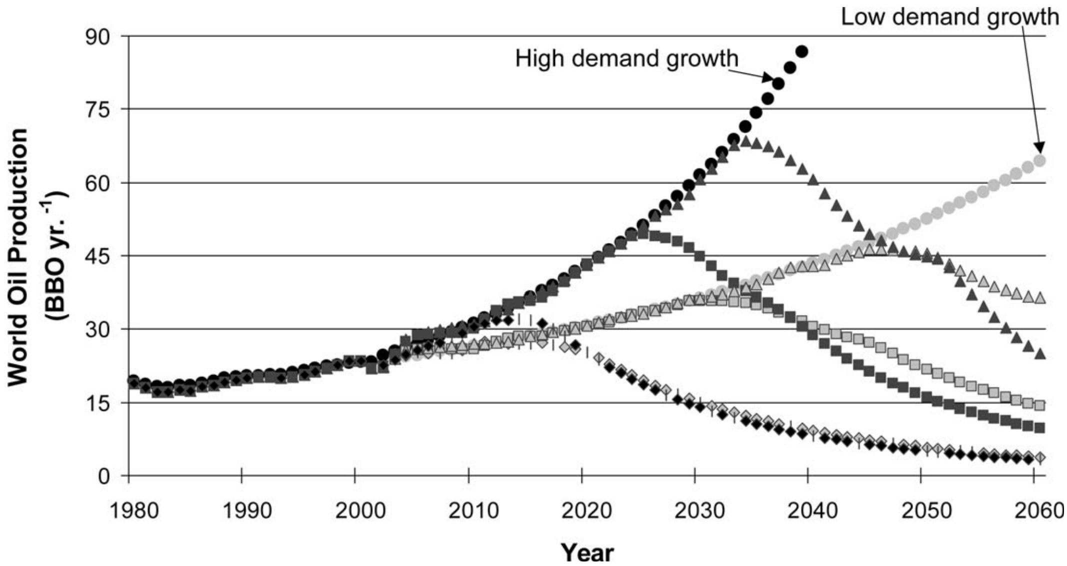

Fig. 3. Forecasted trajectories of world conventional oil production and demand for the period 2002–2060, assuming peak at 50% of EUR extracted and a 15.0% limit on annual growth. Values for 1980–2001 are derived from historical data. ● Historical and forecasted demand assuming high growth. ● Historical and forecasted demand assuming low growth. ▲ World conventional oil production tracking high demand growth, assuming high EUR. △ World conventional oil production tracking low demand growth, assuming high EUR. ■ World conventional oil production tracking high demand growth, assuming medium EUR. □ World conventional oil production tracking low demand growth, assuming medium EUR. ◆ World conventional oil production tracking high demand growth, assuming low EUR. ◇ World conventional oil production tracking low demand growth, assuming low EUR.

there are fewer pre-peak nations at the start of low EUR scenarios, and the constraint of a 5.0% or 7.5% limit on growth in annual production prevents remaining pre-peak nations from increasing production rapidly enough to meet either low or high demand projections. Higher EUR, in turn, caused later and higher peaks in production for any given demand path (Figs. 1–6). We have attempted to model production over the widest possible range of uncertainty by including both the most optimistic estimate to date and the more conservative estimate of global EUR [12,16]. An increase in the EUR estimates of 1.9 to 3 trillion barrels extends the date of peak production by only 15–25 years (Tables 2 and 3, Figs.1–6), depending on the scenario, suggesting that even the unlikely discovery of huge amounts of oil in new or known areas will not extend the period of cheap oil availability by more than two or three decades. Lower limits for growth in annual production caused lower and later peak volumes at the national level, resulting from more oil being retained in the ground and thus a longer time period until 50% of EUR was extracted (Tables 1 and 3). Assuming that the peak production of nations occurred when 60% (vs. 50%) of their EUR had been extracted added 3–9 years to the timing of peak production (Tables 1 and 3, Figs. 1–3 vs. 4–6).

4.3. Other sources of uncertainty

The specific times at which various countries will actually cease to be able to supply oil to the rest of the world, and the actual timing of the decline point of global oil production, can be

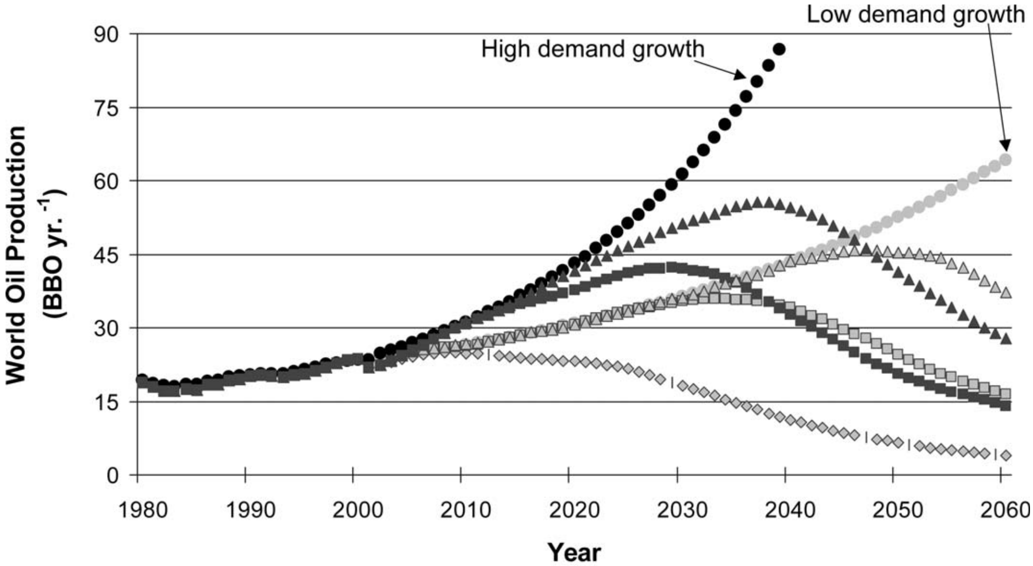

Fig. 4. Forecasted trajectories of world conventional oil production and demand for the period 2002–2060, assuming peak at 60% of EUR extracted and a 5.0% limit on annual growth. Values for 1980–2001 are derived from historical data. Trajectories are the same when assuming low EUR for both high and low demand growth in this case. ● Historical and forecasted demand assuming high growth. ● Historical and forecasted demand assuming low growth. ▲ World conventional oil production tracking high demand growth, assuming high EUR. △ World conventional oil production tracking low demand growth, assuming high EUR. ■ World conventional oil production tracking high demand growth, assuming medium EUR. ▣ World conventional oil production tracking low demand growth, assuming medium EUR. ◆ World conventional oil production tracking high demand growth, assuming low EUR. ◇ World conventional oil production tracking low demand growth, assuming low EUR.

affected by various other sources of uncertainties related to geologic, economic, and socio-political factors. Our forecasts are "pessimistic" in that they do not include unconventional oil (but they do not include these values in consumption either), and optimistic in that they assume that all current and future *probable* reserves will become proven reserves, ignoring the possibility of delays or failures in exploration. Some consider this perhaps too "optimistic" [11]. Furthermore, in the case of the USGS data, we assume that their estimated reserve growth will occur. The USGS and others contend that there are large uncertainties in the estimation of world reserve growth, and that reserve growth may be at least partly an artifact of accounting practices rather than a continued production from old wells [9,16]. This is because of a tendency to confuse revisions of initially conservatively reported proven reserves, with possible reserves growth due to technology advances. Thus, for any given EUR, our forecasts can be considered the best-case scenario, with the date of peak being the latest point at which conventional production can be expected to decrease.

Public domain information on the size of proven reserves of some large producers is often unreliable and there also are large discrepancies within industry data. Much has been made of the fact that in the mid-1980s the oil reserves of essentially all OPEC nations increased by nearly 300 billion barrels with no corresponding large discoveries [32]. Moreover, oil discoveries since 1990 have so far proved quite modest relative to what is required for our mid- and high-

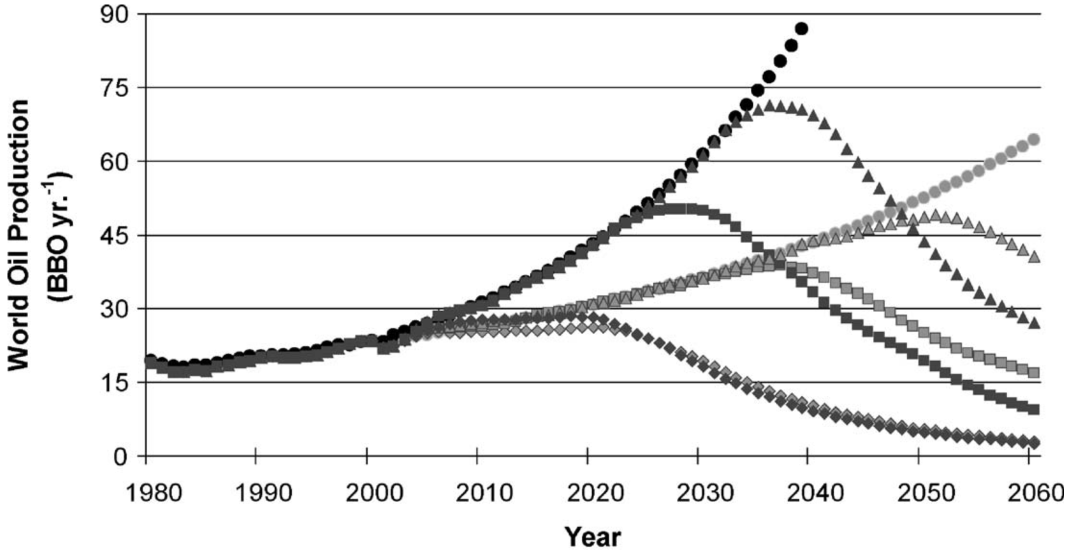

Fig. 5. Forecasted trajectories of world conventional oil production and demand for the period 2002–2060, assuming peak at 60% of EUR extracted and a 7.5% limit on annual growth. Values for 1980–2001 are derived from historical data. ● Historical and forecasted demand assuming high growth. △ Historical and forecasted demand assuming low growth. ▲ World conventional oil production tracking high demand growth, assuming high EUR. △ World conventional oil production tracking low demand growth, assuming high EUR. ■ World conventional oil production tracking high demand growth, assuming medium EUR. ▢ World conventional oil production tracking low demand growth, assuming medium EUR. ◆ World conventional oil production tracking high demand growth, assuming low EUR. ⧫ World conventional oil production tracking high demand growth, assuming low EUR. ◊ World conventional oil production tracking low demand growth, assuming low EUR.

level EUR estimates to be realized, even in the relatively oil-rich Caspian Sea region [33,34]. Any downward revision in any EUR estimates will, all other things remaining equal, lead to an earlier and lower peak in oil production.

The timely development of the remaining reserves of oil could be constrained even before physical limitations become apparent. An important uncertainty is whether remaining pre-peak countries can extract additional oil from existing and future reserves at the rate required to offset both additional global demand and declines in post-peak countries [35]. The large amounts of investment needed to develop drilling and transportation infrastructure may not be forthcoming due to conflicting demands for domestic funds, or a perceived high-risk investment environment that might discourage investors [33,34]. It also may not be in the economic interest of single-resource countries to develop production very rapidly simply to satisfy increased global demand and compensate for declining production in other countries [36]. We approximated the impact of these factors by varying the maximum rate at which production could increase. For any given nation, a constraint on the rate of production increase caused lower and later peak production levels relative to the higher limits, but also earlier dates at which global demand cannot be met. (Tables 1 and 3, Figs. 1–6). The effect of this change varied at the global level. However, higher production growth limits generally caused later and higher peaks in global production, but steeper subsequent declines relative to lower limits (Figs. 1–3 and 4–6). This

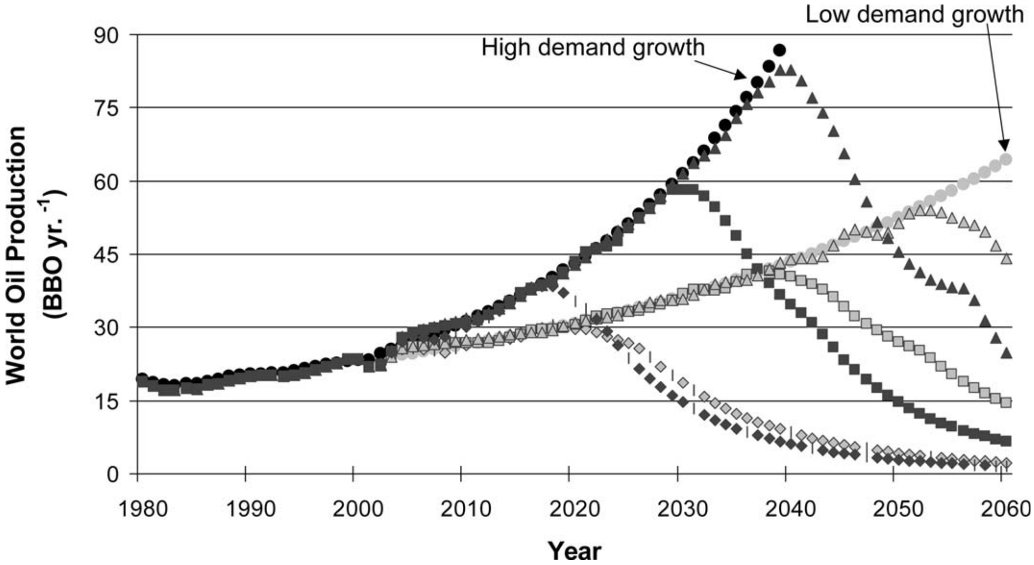

Fig. 6. Forecasted trajectories of world conventional oil production and demand for the period 2002–2060, assuming peak at 60% of EUR extracted and a 15.0% limit on annual growth. Values for 1980–2001 are derived from historical data. ● Historical and forecasted demand assuming high growth. ● Historical and forecasted demand assuming low growth. ▲ World conventional oil production tracking high demand growth, assuming high EUR. △ World conventional oil production tracking low demand growth, assuming high EUR. ■ World conventional oil production tracking high demand growth, assuming medium EUR. □ World conventional oil production tracking low demand growth, assuming medium EUR. ◆ World conventional oil production tracking high demand growth, assuming low EUR. ⧫ World conventional oil production tracking high demand growth, assuming low EUR. ◊ World conventional oil production tracking low demand growth, assuming low EUR.

was because higher limits enabled the remaining pre-peak nations to satisfy annual net global demand increases for a longer period of time.

Changes in global demand patterns can affect domestic production in individual countries substantially. For example, a high growth in global demand causes increased rates of extraction in pre-peak producer countries, shortening the time until they reach peak production, cease exports and eventually face depletion (and the converse). There is no particular reason to assume (as we did in individual scenarios here) that either high or low estimates of EUR will be applicable for any given country. If some of the most important producer countries have less oil than assumed (at any given high or low EUR scenario) then the pressure will increase on the smaller producer nations to increase production sooner.

Some uncertainty relates to the influence of price on the timing of peak production. Since our production estimates are based on the total of *known* and *probable* reserves (EUR), which is probably greater than *economically recoverable reserves*, the total resource brought to markets in our analysis is independent of price. Two scenarios need to be distinguished. The first is a demand-driven increase in oil prices relative to other prices. Such a price increase will tend to increase pre-peak production growth rates by increasing the share of the probable reserve that is economically recoverable. In the alternative scenario, oil price increases would result from the increased energy and capital cost of production of the remaining resources. Earlier work found

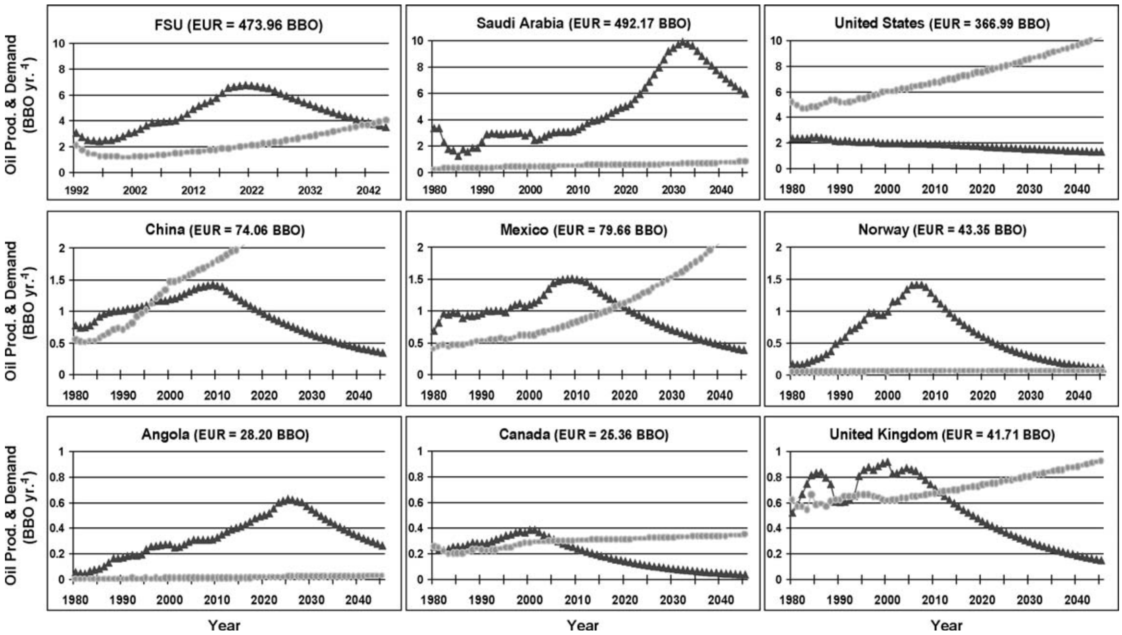

Fig. 7. Forecasted trajectories of conventional oil production (▲) and demand (●) for selected countries for the period 2002–2045. Results are from the scenario assuming medium EUR, low demand growth, national-level peak production occurs when 50% of EUR is extracted, and a maximum rate of increase of 7.5% per year. FSU graph is for period from 1992 to 2045, the post-Soviet era. (Contact J. Hallock for similar figures for additional countries and scenarios.)

that, in general, the energy returned on energy invested (EROI) tended to decline over time for energy resource examined because the most profitable resources are used up first [21,37]. We are not aware of such EROI estimates for different parts of the world, other than general acknowledgements that generating useful products from heavy oils in Venezuela or from tar sands in Alberta requires a very large part of the energy produced as well as substantial supplies of hydrogen from natural gas to make the oil useful. Any large increases in price could lower oil demand and reduce pre-peak production growth rates. Price will, therefore, most likely serve only to modify production trends within the upper and lower bounds established by our results, rather than change them in any fundamental way. Other factors that might constrain demand in the future, such as possible long-term economic recessions, are likely to lower demand growth similarly and therefore production growth [38,39]. Elsewhere, we have called for a new scientific effort to decrease the uncertainty that we represent in our range of scenarios [40].

The very low economic cost of producing, or possibly even finding, new oil supplies in the Arabian Peninsula implies a very high EROI, and hence further rationale for the concentration of production there in future decades. Geo-political factors specific to the Middle East region, however, may complicate development of its oil resources. These include tensions between conservative and even autocratic leaders and both their educated and the uneducated populaces, the great socio-political instability caused by high population growth rates coupled with few economic opportunities or resources beyond oil, and public attitudes surrounding the continuing Israel–Palestine conflict. Added to this is the resentment held by large segments of the populace

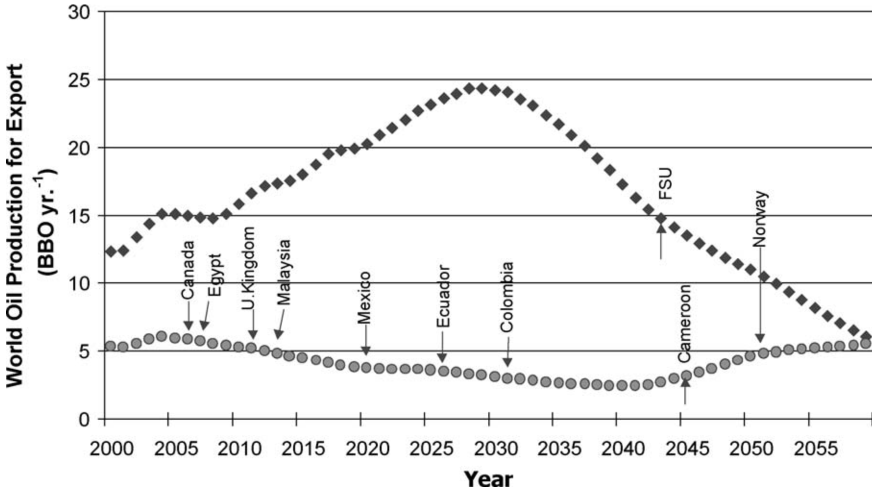

Fig. 8. Forecast of conventional oil production available for export for the world (◆) and non-"Big 7" nations (●) for 2002–2060. "Big-7" nations are the seven largest net-oil producers in 2001 (FSU, Iran, Iraq, Kuwait, Nigeria, Saudi Arabia, and the United Arab Emirates). Oil available for export each year is the sum of net production for all countries. Results are from the scenario assuming medium EUR, low demand growth, national-level peak production occurs when 50% of EUR is extracted, and a maximum rate of production increase of 7.5% per year. Arrows indicate to dates when particular nations cease being net producers.

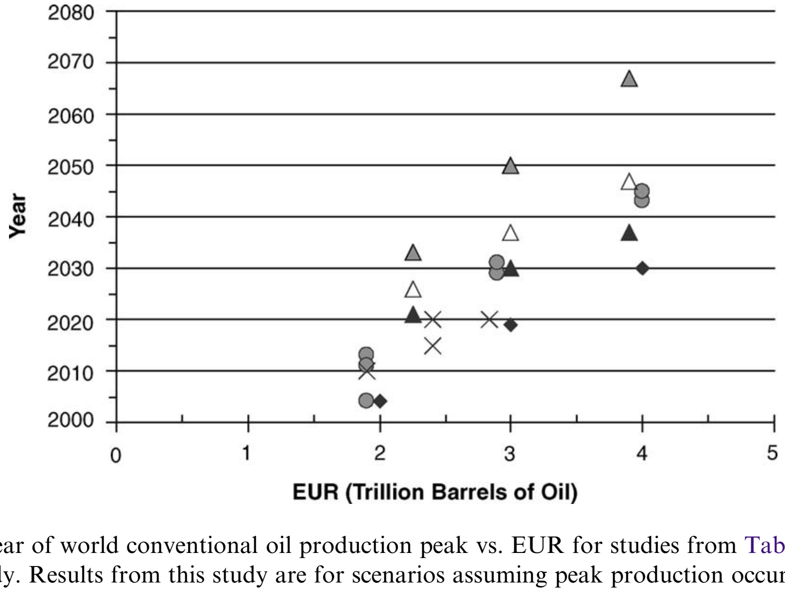

Fig. 9. Forecasted year of world conventional oil production peak vs. EUR for studies from Table 2 and selected scenarios from this study. Results from this study are for scenarios assuming peak production occurs when 50% of EUR has been extracted and LOW growth demand. ◆ Bartlett [9]. ▲ EIA [13]—3% annual growth in production. △ EIA [13]—2% annual growth in production. ▲ EIA [13]—1% annual growth in production. ● This study, depicting results using 5.0, 7.5, and 15.0% annual growth limits. X Alekett and Campbell [12], Cavallo [11] and Edwards [14].

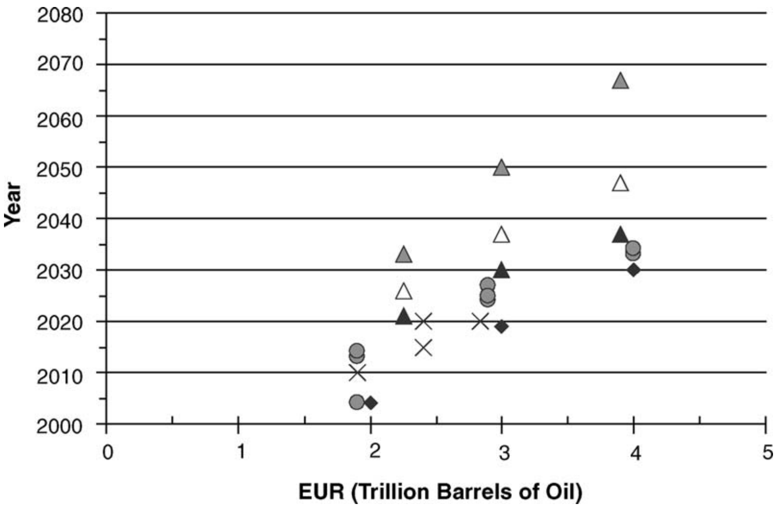

Fig. 10. Forecasted year of world conventional oil production peak vs. EUR for studies from Table 2 and selected scenarios from this study. Results from this study are for scenarios assuming peak production occurs when 50% of EUR has been extracted and HIGH growth in demand.◆ Bartlett [9]. ▲ EIA [13]—3% annual growth in production. △ EIA [13]—2% annual growth in production. △ EIA [13]—1% annual growth in production. ● This study, depicting results using 5.0, 7.5, and 15.0% annual growth limits. X Alekett and Campbell [12], Cavallo [11] and Edwards [14].

in the region generated by their perception of continuing military interventions by major Western powers. There is even the possibility of hostile responses by Middle East nations to any attempt by the Organization for Economic Cooperation and Development (OECD) to reduce their dependency on oil from the Middle East. Such responses could, paradoxically, result in severe oil supply disruption. Politically motivated supply disruptions, whether or not linked to terrorist activity, could result in more oil being kept in the ground for longer in some major oil-producing countries.

Table 3
Changes in the date of and rate of global conventional oil production at the decline-point caused by variation in input parameters of the model

Input variable	Range of input variable	Resultant change in output	
		Year of global decline (years)	Production rate at decline (BBO year^{-1})
EUR	1.9–4.0 TBO globally	12–40	19–40
Percent of EUR extracted at decline point	50–60%	3–9	3–9
Demand growth rate	Low (~1.5%)–high (~3.0%)[a]	0–10	0–16
Annual production growth limit	5.0–15.0%	0–9	5–27

Source: Results of this study.
[a] Demand growth rate percents shown in parentheses are approximate values for the world resulting from the range of country-specific values used.

All of the above-mentioned uncertainties suggest that our assumptions are generally optimistic in that, given the scientific parameters they represent the most rapid extraction of the oil. We assume that roughly half of the oil for each EUR estimate we use is discovered and supplied at relative prices similar to those of today in time to meet the projected demand increases of any given scenario. If oil cannot be discovered in sufficient quantities, the peak in global conventional oil production will occur sooner than a given scenario forecasts. If oil cannot be discovered and exploited quickly enough, for whatever reason, production may not be able to keep pace with rising demand and the peak may be delayed and reduced, (or even hastened if the delay is long enough). If oil cannot be supplied at prices similar to current levels, demand may be retarded and the production peak consequently delayed and reduced. The pattern of net producers becoming net consumers over time has already played out in the case of traditionally important producers such as US, Romania, and China, which were once, but are not now, significant net exporters of oil. There is uncertainty associated with all of our assumptions, and it will be interesting to compare our results (Table 1, Figs. 1–6) with actual consumption and production patterns as they unfold over time. Certainly there is a lot to be said for undertaking further country-by-country and field-by-field analyses as additional data becomes available.

4.4. The role of markets

Some may insist that the irreversible decline in conventional oil production will not bring harsh economic consequences, because society and industry will change easily to unconventional oil and alternative energy sources as price increases make it profitable to do so. This argument assumes market forces will be effective enough to spur the development of viable, competitively-priced alternative sources in time to offset falling conventional production. The potential problem with this reasoning is that price signals associated with the increased scarcity after production peak will occur too late to spur development of these alternatives in time to offset post-peak declines in conventional oil production of 0.1–3.0 BBO $year^{-1}$ or more (Figs. 1–6). Recent efforts to model empirically oil production in the lower 48 US between 1938 and 1991 found that production had stochastic trends that were only weakly correlated with real oil price, average production costs, and rationing [20]. On the one hand, the authors argued that this stochasticity implied that Hubbert's correct 1956 and 1968 predictions of a 1970 peak in lower 48 US oil production based on fitting curves to historical data was fortuitous. On the other hand, their results also implied that the basic Hotelling economic model for depleting an exhaustible resource could not reproduce the historical oil production curve in the lower 48 US [20,41]. So while market-driven activities certainly have their place, it seems imprudent to trust the energy markets by themselves to generate the long term, broad scale solutions on time to meet the real energy needs of the poor, maintain reasonable expectations for the affluent and those hoping to become affluent, and achieve a stable climate.

4.5. The way forward

Our principle finding that we hope will attract the attention of policy makers is that it is impossible to say whether our early or later forecasts of the production decline point will be closer to reality. The decline point could occur in 2037 or in 2004. Following the precautionary principle would seem prudent at this point, especially because most of the oil resources necessary for the decline point to occur in 2037 have not been discovered yet. Given the relatively long turnover time for both energy supply technologies and end-use infrastructure [4], policy decisions need to be considered with some urgency. We end our analysis with a list of policy issues warranting consideration.

1. The timing and magnitude of the peak depends most importantly on estimates of EUR, which vary greatly from one source to another. It is not yet possible to evaluate the accuracy of high and low estimates provided by what appear to be equally qualified professionals. In particular, the USGS estimates appear considerably higher than most others. This is a critically important issue which should be subject to scientific inquiry over time at field by field, country by country, and global levels, which needs to be done professionally and in the public domain [40]. Since most of the production is from a relatively few hundred large fields, the issue is not daunting. These data are far too important to the general public to be shielded from professional analysis and public inquiry. Within this overall context it is important to pay close attention to definitions: what is "proved", what does "probable" mean, what recovery efficiencies are assumed and realized, and at what energy cost, and so on.
2. Improvements in oil field technology and in oil production as a consequence, need to be understood much better from the perspective of the degree to which the activity is adding to total reserves vs. extracting known or probable reserves more rapidly.
3. Net energy for oil and other fuels, EROI, and the relation between price and net energy gained needs to be calculated, for different regions, countries and fields.
4. The public and its political representatives seem to feel that the market has resolved the "energy crises" of the 1970s. This is an extremely dangerous assumption, for the next major "energy crisis" will almost certainly be more stifling and less tractable than previous ones. The "fact" that oil seems to continue to be found at high rates is mostly a consequence of original conservative reporting as most "new" oil comes from reassessing existing, and often very old, fields as development drilling proceeds. Again, public exposure to and discussion of formerly proprietary data, especially discovery data, will help raise awareness of an impending peak. The volume of oil discovered globally per year peaked in the 1960s and has declined ever since. Unless the rate of oil discovery increases very rapidly or substantial reserve growth is evident very soon, we are skeptical that the production increases forecasted in many of our scenarios can be achieved.
5. The world is going to be increasingly dependent on fewer and fewer exporters of conventional oil located mostly in the Middle East and nearby regions. Continued political instability in these regions may pose severe challenges in the coming decades to conventional oil output and export availability. These challenges will be intensified by domestic economic development in conventional oil producing countries, which will increase their use of locally extracted oil and oil products. Policies of oil importing countries will need to be more sensitive to the needs and aspirations of long-term oil exporting countries while simultaneously pursuing appropriate alternative sources of energy (especially renewable sources available in the quantities the world will require) to replace conventional oil.
6. There is a need for developing new energy policies that are based on sustainability principles [42] and that combine concerns about supply constraints with environmental concerns asso-

ciated with the use of oil and especially its alternatives. Such policies should address the need to reduce the transportation sector's overwhelming use of, and reliance on, oil products [1,43] and establish mechanisms that will foster the accelerated commercialization of viable renewable energy options such as, perhaps, solar-generated hydrogen [44].

7. Economic growth, sought by essentially all governments, needs to be seen in its relation to the future availability of energy [2]. Assuming that economic growth can be predicated on increasing oil consumption for much longer appears questionable. Because much of the increase in demand for oil in the near future will occur in developing countries, there is also an urgent need for international programs that will transfer technology and development concepts aimed at fostering energy efficiency and alternate fuel technologies from developed to developing countries.
8. Energy, including especially its basic nature, sources and relation to economic and environmental issues has to re-enter our university curricula as a discipline as basic, widely taught and worthy of study as biology, economics or geology [2]. We need to critically examine the appropriateness of using neoclassical models to make judgments about future oil supply and the role of markets. Economics was once, and should be again, as much a biophysical science as it is a social science; constructing a reasonable biophysical economic approach would be of great utility [2,45].
9. The public needs much greater exposure to this issue, particularly the scientific achievements, and simply the current state of affairs regarding oil resources and production than it has had in the recent past. Perhaps running records of oil production might be displayed in high quality scientific outlets in the same way that stock prices are routinely displayed, as the oil data is a far better predictor of economic health than the stocks, at least in the long run. For example, it appears oil production in the UK has been declining more steeply since 1999 than many oil analysts had expected, and Norway may have peaked in 2001.
10. Finally, we need to have a much better discussion of these issues as part of our political dialogue.

Vast reserves of oil have been a dominant contributor to the past 100 years of unparalleled growth in affluence for a large segment of the world's population. The trend we have identified of a geographic concentration of production followed by an irreversible global production decline has the potential to cause wide-ranging socio-economic disruption. The minimization of the impacts of these declines, while ensuring sufficient access to cheap energy for both the developed and developing sections of the world's population, will be a great challenge.

Acknowledgements

We thank Sergio Ulgiati and others at the Third Bi-annual Conference on Energy, Porto Venere Italy for stimulating discussions on the topic, Jean Laherrère for insights into the functioning of the oil industry and for directing us to the recent ASPO data [12], and Nathan Gagnon and Alexis Krukovsky for help with data acquisition. Three anonymous reviewers contributed significantly to our understanding and helped improve the clarity of this document.

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