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Have we run out of oil yet? Oil peaking analysis from an optimist's perspective ☆

David L. Greene*, Janet L. Hopson, Jia Li

Oak Ridge National Laboratory, National Transportation Research Center, University of Tennessee, 2360 Cherahala Boulevard, Knoxville, TN 37932, USA

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Abstract

This study addresses several questions concerning the peaking of conventional oil production from an optimist's perspective. Is the oil peak imminent? What is the range of uncertainty? What are the key determining factors? Will a transition to unconventional oil undermine or strengthen OPEC's influence over world oil markets?

These issues are explored using a model combining alternative world energy scenarios with an accounting of resource depletion and a market-based simulation of transition to unconventional oil resources. No political or environmental constraints are allowed to hinder oil production, geological constraints on the rates at which oil can be produced are not represented, and when USGS resource estimates are used, more than the mean estimate of ultimately recoverable resources is assumed to exist.

The issue is framed not as a question of "running out" of conventional oil, but in terms of the timing and rate of transition from conventional to unconventional oil resources. Unconventional oil is chosen because production from Venezuela's heavy-oil fields and Canada's Athabascan oil sands is already underway on a significant scale and unconventional oil is most consistent with the existing infrastructure for producing, refining, distributing and consuming petroleum. However, natural gas or even coal might also prove to be economical sources of liquid hydrocarbon fuels.

These results indicate a high probability that production of conventional oil from outside of the Middle East region will peak, or that the rate of increase of production will become highly constrained before 2025. If world consumption of hydrocarbon fuels is to continue growing, massive development of unconventional resources will be required. While there are grounds for pessimism and optimism, it is certainly not too soon for extensive, detailed analysis of transitions to alternative energy sources.

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Keywords: Oil depletion; Oil peaking; Energy transition

1. Introduction

Petroleum is the most critical energy resource for modern economies, supplying about 40% of the world's primary energy and nearly all of the fuel for the world's transportation systems. Over the past 30 years, world oil use has increased by 47% despite oil price shocks and economic downturns. Over the next 30 years oil demand is expected to grow by 60% as the transportation systems of developing economies become increasingly motorized (International Energy Agency (IEA), 2002a, Table 2.1). This growing reliance on oil and the continuing lack of economical substitutes for petroleum-based transportation fuels has generated concern about the future adequacy of the world's petroleum resources.

The debate over oil resources is generally framed in terms of "pessimists" who foresee an imminent peaking of world oil production (e.g., Bentley, 2002; Deffeyes, 2001; Campbell and Laherrere, 1998) versus "optimists" who expect innovation and market forces to make the question of oil resource limitations irrelevant (e.g., Odell, 1999; Adelman, 2003). Of course, many fall somewhere between these two viewpoints (e.g., Davies and Weston, 2000; Wood et al., 2000; Cavallo, 2002). The pessimists' analysis is based on "peaking curves" for individual petroleum deposits, using methods derived from the seminal analysis

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*Corresponding author. Tel.: +1 865 946 1310; fax: 1+ 865 946 1314.

E-mail addresses: dlgreene@ornl.gov (D.L. Greene), hopsonjl@ornl.gov (J.L. Hopson), lij1@ornl.gov (J. Li).

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of Hubbert (1956) who accurately predicted the peaking of US oil production. The pessimists are sometimes referred to as ''geologists'' because of their belief that geology will be more important than economics or technology in determining when oil production will peak. The optimists are often referred to as ''economists'' because of their belief that markets and technological change will make the scarcity of oil an irrelevancy.

The debate is important because a sudden, unanticipated and permanent decline in world oil production would severely damage world economies, probably for a decade or longer. In addition, the transition from oil to some other source of energy for transportation is almost certain to have important economic, environmental and security implications. A transition to more carbon intensive fossil energy sources would increase the likelihood of major climate changes. As several have pointed out, the longer-term problem of climate change depends on the world's decision to burn or not to burn the world's vast fossil resources of coal and unconventional oil and gas and release the carbon to the atmosphere. There is not enough carbon in all the world's conventional oil and gas resources to raise atmospheric carbon concentrations above the threshold of 450 ppm (Grubb, 2001, p. 838). Knowing more about when and how rapidly such a transition might occur could allow nations to plan for a more desirable path.

This paper describes a quantitative analysis of oil peaking from the perspective of an optimist including the potential for developing alternative sources for liquid fuels. To date, most quantitative analysis of the oil peaking issue has been done by the pessimists. This is logical, since from the optimists' perspective, why waste time analyzing an irrelevancy? A premise of this study is that if a quantitative analysis of the oil peaking issue from the optimists' viewpoint shows that it is neither so distant in time nor so gradual that negative impacts can be safely neglected, then understanding oil peaking and the consequent transition to alternative sources of energy should be a critical priority for energy policy research.

The analysis makes an effort to incorporate uncertainty along three dimensions: (1) alternative scenarios of future oil demand, (2) alternative assessments of the extent of world oil resources, and (3) risk analysis of rates of technological change, reserve growth, resources discovery and Middle East oil production.

2. Background

Concerns about resource availability can be traced back in time at least as far as Thomas Malthus' *An Essay on the Principle of Population*, which argued that population growth would be limited by the availability of tillable land (e.g., Tilton, 2003). More recently, Meadows et al. (1972) explored the potential impacts of resource scarcity and pollution on world economic and population growth using simulation modeling. Their study is most famous for its prediction that ''under the assumption of no major change in the present system, population and industrial growth will certainly stop within the next century, at the latest.'' (Meadows et al., 1972, p. 126). What is frequently overlooked is the study's finding that major changes in technology and environmental policy could alter that conclusion.

M. King Hubbert (1962) observed that individual oil fields followed an approximately bell-shaped curve of rising and then declining production. Extending this concept to the region of the lower 48 United States, he correctly predicted that US oil production would peak within a decade; it peaked in 1970. Since then, ''pessimists'' such as Campbell and Laherrere (1998), Bentley (2002) and Deffeyes (2001) have further developed Hubbert's methods, applied them to the entire world, and generally concluded that world oil production will peak by 2010.

3. What is oil?

In any assessment of oil resources, the first question that must be answered is, ''What is oil?'' (Laherrere, 2001). In this analysis, two kinds of oil are distinguished: conventional and unconventional. Conventional oil includes liquid hydrocarbons of light and medium gravity and viscosity, occurring in porous and permeable reservoirs. Here, oil available with enhanced recovery is considered conventional; Rogner (1997) and Laherrere (2001) take a different view. Also, conventional oil resources here include natural gas liquids. Unconventional oil comprises deposits of greater density than water (heavy oil), viscosities in excess of 10,000 cP (oil sands), and occurrences in tight formations (oil shale). Ultimately, the distinction between conventional and unconventional resources is based on technology and economics. Fifty years ago, offshore crude oil was considered an unconventional resource (Adelman, 2003). Some today consider Canadian oil sands to be conventional oil, although here they are classified as unconventional here due to the cost and complexity of operations, water scarcity, and the need for dilution or upgrading before the product can be shipped (Economist, 2003).

Unconventional oil is not the only potential source of energy to replace petroleum. Liquid hydrocarbon fuels can be made from any resource containing carbon, including coal or biomass. Much attention has recently been given to the possibility of powering transportation vehicles with hydrogen fuel cells (US Department of Energy (US DOE), 2002). This analysis allows a transition only to unconventional petroleum, not because that is the only possibility, but for simplicity and because it is almost certainly the path of least resistance in terms of infrastructure, economics and policy. Indeed, the development of Canadian oil sands and Venezuelan heavy oil suggest that the transition to unconventional oil is underway.

Another premise is that world oil resources are known well enough to permit a meaningful analysis of their depletion. As more regions of the world are explored, as more oil is produced, and as the science of geology advances, it is reasonable to expect that estimates of the total quantity of world oil resources would stabilize. Sixty years of world oil resource assessments are plotted in Fig. 1 (Alberta Chamber of Resources (ARC), 2003). While there is still considerable disagreement among recent estimates, it is significant that assessments made since 1960 do not show an upward (or downward) trend. Apparently, differences in assumptions, definitions and premises are causing the dispersion, rather than increasing knowledge of the earth's crust over time.

In the year 2000, the US Geological Survey (USGS) published a comprehensive assessment of the world's conventional oil resources, produced, discovered and undiscovered, including a first-ever estimate of the potential for reserve growth due to technological change and other factors (US Geological Survey (USGS), 2000). The resulting mean estimate of 3.0 trillion barrels (Table 1) is high relative to most previous estimates and even in comparison to the USGS' prior estimate of 2.4 trillion barrels (Masters et al., 1994). Essentially all of the difference, however, is due to the inclusion of a new category of oil resource, reserve growth, amounting to 0.7 trillion barrels. The USGS (2000) assessment also explicitly included uncertainty. Ninety-five percent and 5% probability estimates are also provided, ranging from 2.2 trillion up to 3.9 trillion barrels. When natural gas liquids are added the range of estimates for total petroleum resources becomes 2.5–4.4 trillion barrels, with a mean estimate of 3.3 trillion.

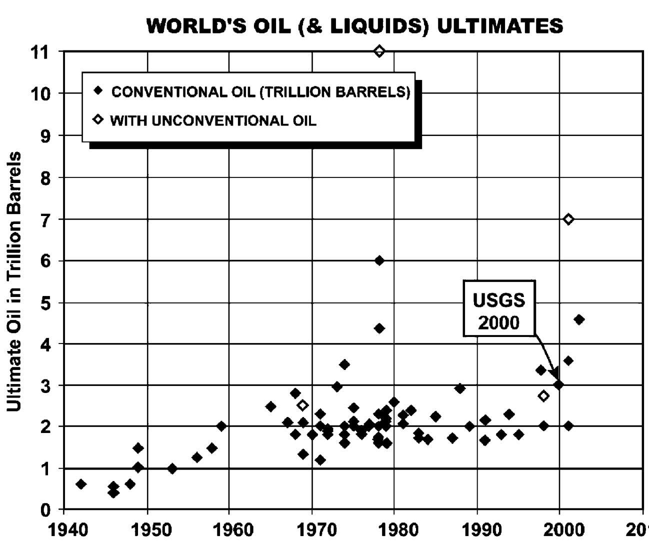

Fig. 1. World's oil (& liquids) ultimates. *Source*: Ahlbrandt et al., 2005.

The pessimists believe that the USGS (2000) assessment overestimates conventional oil resources. First, they point out that estimates of proved reserves should not be taken at face value (as done in the USGS study) and, in particular, the estimates for key OPEC members are inflated because possession of reserves confers bargaining power within OPEC. Campbell (1997) has put the extent of overstatement at about 360 billion barrels, about 35% of total OPEC proved reserves. Second, they note that while official proved reserve estimates in the US underestimate the ultimately recoverable resource in place, they believe that the petroleum geologists' resource estimates upon which their analyses are based will show little reserve growth. Third, the USGS relied on US reserve growth experience in developing estimates for the rest of the world. The pessimists argue that the rest of the world lists as proven what the US considers proven plus probable reserves. Thus, applying US reserve growth experience to the rest of the world will result in inflated projections of ultimate resources. The USGS geologists have counter arguments, but resolving the issue is outside the scope of this study. As an alternative to the USGS (2000) world oil resource estimates, we use the estimates derived from Campbell (2003) shown in Table 2. These put total conventional oil (including natural gas liquids) at 2.4 trillion barrels, and show only 300 billion barrels of unconventional oil.

4. Unconventional oil

The USGS (2000) study did not estimate the extent of unconventional oil resources. Estimates were derived from other USGS reports (Dyni, 2000), as well as reports of the World Energy Council (World Energy Council (WEC), 2001) and International Energy Agency (International Energy Agency (IEA), 2002b) and compared to estimates published by Rogner (1997). Details may be found in Greene et al. (2003).

Table 1
Estimates of world petroleum resources for the year 1996 from the USGS (2000) study

	Oil				Natural gas liquids				Total petroleum			
	95%	50%	5%	Mean	95%	50%	5%	Mean	95%	50%	5%	Mean
Undiscovered	394	683	1202	725	101	196	387	214	495	879	1589	939
Res. growth	255	675	1094	675	26	55	84	55	281	730	1178	730
Proved res.	884	884	884	884	75	75	75	75	959	959	959	959
Cum. prod.	710	710	710	710	7	7	7	7	737	737	737	717
Total	2244	2953	3890	2994	210	334	553	351	2454	3287	4443	3345

Unconventional oil reserves appear to be highly concentrated in a few regions. The WEC makes the following observation about oil sands and heavy oil.

> Although natural bitumen and extra-heavy oil are worldwide in occurrence, a single extraordinary deposit in each category is dominant. At Alberta, Canada, natural bitumen deposits comprise at least 85% of the world total bitumen in place, but are so concentrated as to be virtually the only such deposits that are economically recoverable for conversion to oil. The deposits amount to roughly 1700 billion barrels of bitumen in place. Similarly, the extra-heavy crude oil deposit of the Orinoco Oil Belt, a part of the Eastern Venezuela basin, represents nearly 90% of the known extra-heavy oil in place. (WEC, 2001, Chapter 4).

This assertion is partly contradicted by an IEA (2002b) report, which shows 1350 billion barrels (197 Gtoe) of extra-heavy crude and/or bitumen in place in Russia, but reports no estimate of how much of this resource in place is ultimately recoverable. The US owns most of the world's known shale oil. The WEC (2001, Ch. 3) reports 3.34 trillion metric tonnes of oil shale in-place in the US, from which 60–80 billion metric tonnes of oil are deemed recoverable reserves with a roughly equal amount of "estimated additional" reserves.

World shale oil resources have been estimated by the USGS at 2.6 trillion barrels (376 Gtoe) in place (Dyni, 2000). The estimate is considered conservative because many oil shale deposits have not been fully investigated and some countries do not report them at all. The estimated ultimate resources of unconventional oil used in this study are shown in Table 3.

Because unconventional oil resources have been of little economic interest, the extent of unconventional oil resources is highly uncertain, as are the costs of development for anything but Venezuelan extra-heavy oil and Canadian oil sands.

In the analyses presented in this paper, two alternative oil resource estimates are used.

- USGS (2000) conventional oil estimates plus the unconventional oil estimates synthesized from USGS/WEC/IEA as described above, and
- Estimates based on Campbell's (2003) year-end 2002 global assessment.

The USGS estimates reflect the following premises: (1) that technological progress will significantly expand ultimate resources and (2) that there is considerable uncertainty about how much oil remains to be found. Campbell is less sanguine about the ability of technology to expand resources and his data reflect far less uncertainty about how much oil remains.

Table 2
Estimates of world conventional and unconventional oil resources by Campbell, at year end 2002

Resource category	Estimated quantity (Billion barrels)
Conventional oil	
Known fields produced	896
Known fields future production	871
New fields future production	133
Deepwater future	60
Polar future	30
Gas liquids	400
Total conventional	**2390**
Heavy oil (*Unconventional*)	**300**

Source: Campbell (2003).

Table 3
Estimates of world oil sands and oil shale resources from three sources

Region	IEA/WEC/USGS			Rogner	
	Oil shale (Gtoe)	Heavy oil & oil sands (Gtoe)	Share heavy oil & oil sands (%)	Total unconv. (Gtoe)	V + VI unconv. (Gtoe)
Canada	1.1	45.3	97.7	46.4	45.3
USA	154.8	4.2	2.7	159.0	61.1
LAM	9.7	39.5	80.3	49.1	94.1
FSU	6.5	39.5	85.9	46.0	22.7
EEU	0.0	0.0	19.3	0.0	0.5
AFR	7.3	0.6	7.7	7.9	6.5
MEA	30.5	2.3	7.1	32.8	61.9
PAO	37.0	0.0	0.0	37.0	29.5
PAS	0.8	0.0	0.0	0.8	5.4
WEU	6.9	0.0	0.0	6.9	8.9
CPA	1.2	0.0	0.0	1.2	44.5
SAS	0.1	0.0	0.0	0.1	0.4
World	255.9	131.4	33.9	387.3	380.8

Rogner's estimate of 106.4 Gtoe of category V and VI unconventional oil for North America has been divided between Canada and the USA by assuming that all Canadian oil sands are included and no Canadian oil shale. This leaves 61.1 Gtoe of category V and VI oil shale for the USA.

5. Method of analysis

The transition model takes a pre-existing scenario of world energy production and use to 2050 as a starting point, performs an initial accounting for the availability of conventional oil by region and the likely need for unconventional oil worldwide, calibrates world oil supply and demand curves to the scenario using regional depletion-cost functions and assumed price elasticities, then solves for equilibrium supplies and demands for conventional and unconventional oil by region. The resulting production estimates by region are again passed to the accounting model for final calculations of the depletion of conventional oil and the transition to unconventional resources (Fig. 2). The details of this model can be found in Greene et al. (2003).

6. Resource accounting

Proved reserves are the stock from which current production is drawn and to which additions are made from other resource categories (Fig. 3). If a scenario's production requirement for a region can be met from its proved reserves, the full amount of the requirement is withdrawn. A region is considered unable to meet a production requirement if the ratio of its proved reserves (R) to the production requirement (P) is below a user-specified target reserves-to-production $(R/P)^*$ ratio. At that point, production is constrained to converge toward the target $(R/P)^*$ ratio. The unproducible requirement is set aside as potential demand for unconventional oil.

The "target R/P" approach will not satisfy advocates of the Hubbert theory, who would point out that it will not be possible for regions to continue increasing production, or even hold it constant beyond the 50% depletion point (e.g., Bentley et al., 2000). On the other hand, economists might argue that the Hubbert theory is overly mechanistic and that if peaking ever occurs it will be determined more by economics and technology than geology (e.g., Odell, 1999). The R/P ratio rule was used by the Energy Information Administration (Wood et al., 2000) in its analysis of the potential peaking of world oil production. It is clear from Wood's peaking curves that if world producers really followed a strict R/P rule, sharp production peaks and catastrophically rapid transitions could result. Cavallo (2002) also used the R/P ratio to estimate the time at which world oil production might peak but he defined reserves differently, as the USGS estimates of proved plus undiscovered resources. He termed this the R_{P+U}/P ratio, and concluded that production in a region would begin to

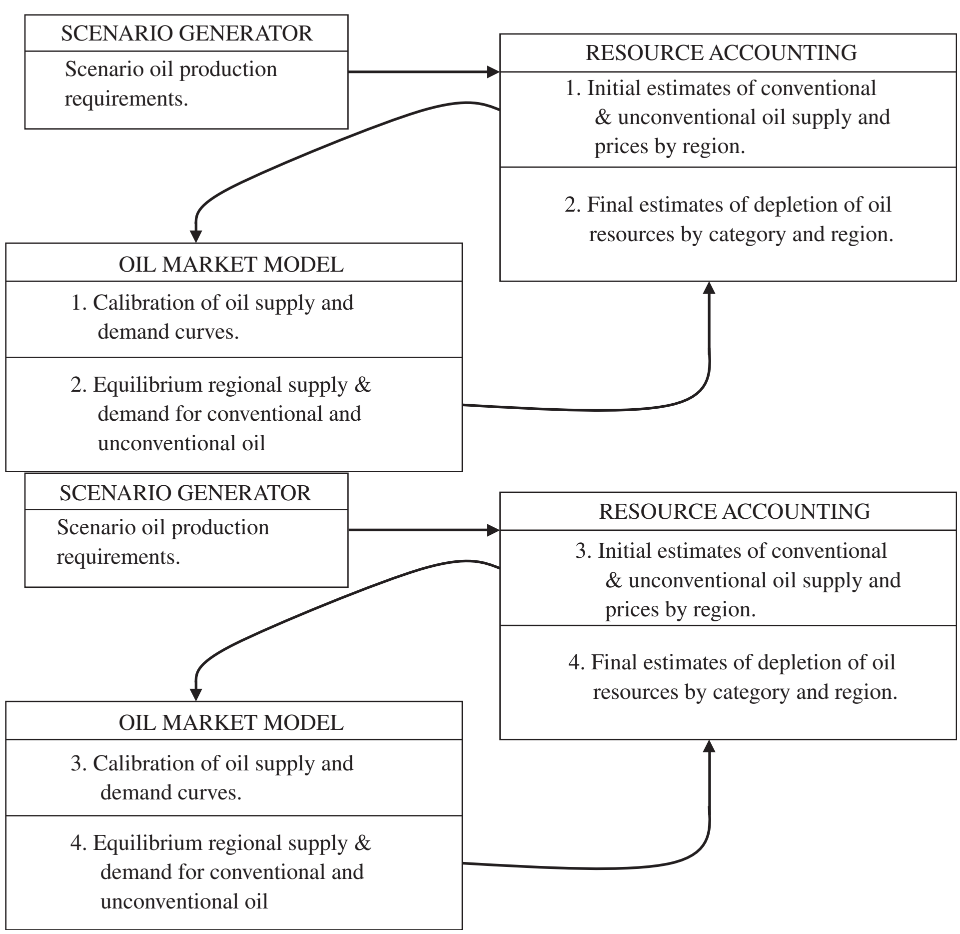

Fig. 2. Flow diagram of World Energy Scenarios model.

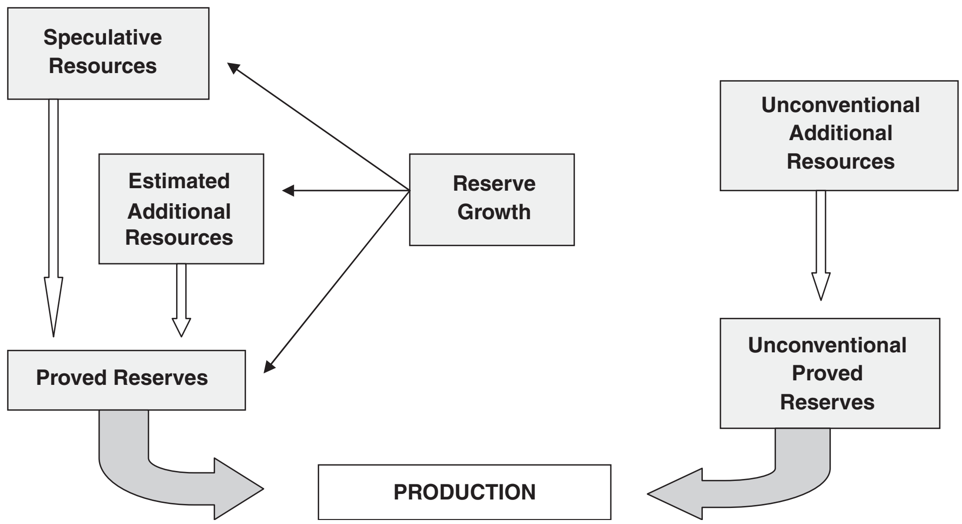

Fig. 3. Structure of Resource Accounting model.

decrease when the ratio was somewhere between 10 and 15. The (R/P) ratio might best be thought of as a rule-of-thumb specifying that producers will not invest in increasing output when the lifetime of the investment would be shorter than $(R/P)^*$ years.

Proved reserves are continuously augmented by additions from speculative and estimated additional resources, as well as from reserve expansion (as illustrated in Fig. 3). They are an inventory, "continuously replenished by investment in new and old fields" (Adelman, 1990, p. 9). The rates of additions from estimated additional, and speculative resources, as well as from reserve expansion are parameters of the analysis, but the total quantities of conventional oil available from these sources are treated as a fixed stock. The size of that stock, however, depends on the resource assessment and technological change parameters.

Withdrawals from proved reserves are primarily replenished by flows from *estimated additional* reserves. Estimated additional reserves are the 50th percentile undiscovered oil estimate for the USGS data, and simply the sum of new fields, and deepwater and polar future fields, for Campbell's data. The inflow from estimated additional reserves equals the current year's production from proved reserves if adequate estimated additional reserves exist.

Speculative resources are developed and added to proved reserves according to a user-specified bell-shaped curve. For the USGS estimates, speculative resources are defined as the difference between the 50th and 5th percentile undiscovered oil estimates. There is no corresponding category when Campbell's estimates are used. Like other conventional oil resources, speculative resources expand over time due to reserve growth. The inclusion of this category implies a degree of optimism.

All three types of conventional resources (proved, estimated additional and speculative) are augmented by reserve growth at a user-specified annual rate. This is intended to represent the combined effects of learning and technological advances on recovery rates. As long as there are remaining resources in the reserve growth category, it continues at the specified rate. Details can be found in Greene et al. (2003).

A potential call on unconventional oil is generated when a region is unable to supply the oil production specified by a scenario from its conventional oil reserves. An oil production deficit is created for that region in that year and conventional oil production deficits are summed over all regions to obtain a global conventional oil production deficit. The global oil production deficit can be satisfied by either conventional oil from other regions or unconventional oil depending on supply costs. If unconventional oil is expensive, the deficit will shift towards less expensive conventional oil produced in regions with larger, cheaper conventional oil reserves. Whereas Middle East conventional production is exogenous following Cavallo's (2002) method, Middle East production of unconventional oil is endogenous.

If world resources of even unconventional oil are inadequate the price of oil will rise until supply equals demand. There is no "backstop" energy source beyond unconventional oil. In reality, of course, coal, natural gas, or biomass could be used to produce liquid fuels.

7. Simulating a transition to unconventional oil

Logistic depletion/cost curves (Rogner, 1997) represent the long-run *marginal* cost of discovering, producing and delivering a barrel of oil to the market as a function of the fraction of a region's ultimate resources that have already been produced. For conventional oil, all regions were assumed to have the same slope parameter while the heights of regional curves at a given percent depletion were calibrated to a limited amount of data available on regional production costs (e.g., International Energy Agency (IEA), 2001, p. 54; Stauffer, 1994). Two unconventional oil

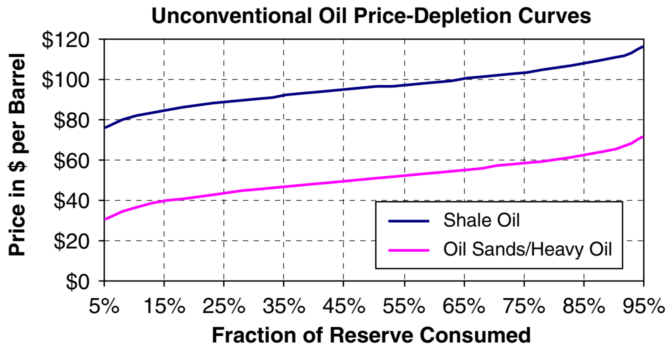

Fig. 4. Unconventional oil price–depletion curves.

depletion cost curves are assumed: one for regions dominated by oil sands/heavy oil and another for oil shale dominated regions (Fig. 4). These are calibrated to assume initial production costs and the world unconventional oil depletion status in 2000 (about 1%). The heights of all three types of curves (conventional oil, oil sands + heavy oil, shale oil) decline over time at different assumed rates, representing the effect of technological progress on the costs of exploration and development. Thus, it is possible for costs of production to rise, fall or remain constant as oil resources are depleted. The use of these curves is admittedly a severe simplification of the economics of long-run regional oil supply.

The Middle East and North Africa (MEA) region, comprised chiefly of OPEC members, is not represented by a supply function. Instead, its supply of conventional oil is treated as exogenous. For the risk analysis simulations, a probability distribution of annual rates of growth in MEA conventional oil supply was assumed.

The methodology of this analysis is intended to reflect the optimists' view of the oil depletion issue. It does not make use of Hubbert curves, but allows regional oil production to increase until the target resource-to-production ratio is reached. The category of speculative resources reflects the view that more than the 50th percentile estimate of undiscovered oil will be found. In addition, no oil resources are considered off limits for environmental or other reasons. The analysis may be pessimistic in the sense that it cannot imagine the full possibilities for technological change.

8. Descriptions of scenarios

World energy use and supply scenarios were taken from the IIASA/WEC study, *Global Energy Perspectives*, (Nakićenović et al., 1998) and from forecasts of international energy use to 2020 by the US Energy Information Administration (US Department of Energy and Energy Information Administration (US DOE/EIA), 2002).

Two IIASA/WEC scenarios are used here: (1) Case A1, a variant of the "high growth" scenario in which "technological change focuses on tapping the vast potential of conventional and unconventional oil and gas occurrences" (Nakićenović et al., 1998, p. 8), and (2) Case C1, a variant of the "ecologically driven" scenario in which unprecedented international cooperation to protect the environment results in large increases in energy efficiency and renewable energy use, but little adoption of nuclear energy. While these scenarios were developed all the way to 2100, only the portions up to 2050 are used here.

Table 4
IIASA/WEC global energy scenarios

		High growth A	Ecologically driven C
Population (billions)	1990	5.3	5.3
	2050	10.1	10.1
Gross world product (trillion 1990 US$)	1990	20	20
	2050	100	75
Primary energy intensity improvement (%/year)	1990–2050	−0.9%	−1.4%
Primary energy demand (Gtoe)	1990	9	9
	2050	25	14
Oil, primary energy use (Gtoe)	1990	3	3
	2050	8	3

Source: Nakićenović et al. (1998), Tables 2.1 and 5.1.

In both scenarios, world population grows from 5.3 billion in 1990 to 10.1 billion by 2050 (Table 4).[1] Gross world product (GWP) increases from $20 trillion (1990 US$) in 1990 to $100 trillion in the high growth A scenario, and to $75 trillion in the ecologically driven C scenario. Total world primary energy use increases from 9 to 25 Gtoe in the A scenario and from 9 to 14 Gtoe in the C scenario. Much of this growth occurs in the world's developing regions. Both scenarios assume substantial decreases in the energy intensity of GWP: −0.9%/yr. for A and −1.4%/yr. for C. Oil use grows at a slightly slower rate than total energy in the A scenario, and in the C scenario oil use increases modestly, then falls back to its 1990 level by 2050.

Developed from a base of 1990, the IIASA/WEC scenarios are already somewhat out of sync with actual year 2000 energy consumption and production. This is particularly true of the C1 scenario, but even the A1 scenario anticipated much lower petroleum use than has actually occurred, especially in North America. To calibrate the scenarios to actual 2000 data, and in order to substitute a more "conventional" view of the evolution of world energy markets through 2020, the scenarios were adjusted to match US Energy Information Administration Annual Energy Outlook 2002 forecasts to 2020. The A1 scenario was calibrated to the AEO 2002 Reference Case

[1] Since the IIASA/WEC study was completed, the UN has revised its population projections downwards to 8.9 billion in 2050 as a medium estimate and 10.6 billion as a high estimate.

through 2020. The C1 scenario was calibrated to the AEO 2002 "low growth" projection. After 2020, a splining method (see Greene et al., 2003) was used to trend the projections back towards the appropriate IIASA/WEC scenario.

In the IEO 2002 Reference Case, world energy use increases from 8.7 Gtoe (350 quads, at 40.4 quads/Gtoe) in 1990, to 9.6 Gtoe in 1999 and 15.4 Gtoe by 2020 (US DOE/EIA, 2002, Table A1). In the developing economies energy use increases from 2000–2020 at an average annual rate of 3.7%, nearly three times the rate of growth in energy use of industrialized countries over the same period. World oil use increases in the Reference Case at an annual rate of 2.2%, about the same as overall energy use. About two-thirds of the total world increase in oil use is accounted for by growth in developing country demand.

Even after calibration to the IEO 2002 projection through 2020, oil use in North America is quite low in 2050. According to the IIASA/WEC A1 scenario, North American oil use increases from 834 Mtoe in 1990 to 899 Mtoe (7.8%) in 2020 and then decreases to 879 Mtoe by 2050. In reality, US petroleum use increased 16% from 1990 to 2000. The IEO 2002 Reference projection anticipates a further 35% increase by 2020, for an overall increase of 55% over 1990. Projecting a decline over the next 30 years to 10% below the year 2000 level does not seem reasonable for a reference case. For this reason, North American oil use projections based on the Champagne model (Natural Resources Canada (NRCan), 2002; Energy and Environmental Analysis (EEA), 1999) have been substituted for the IIASA/WEC scenarios' North American oil use projections (Fig. 5). The key components of the three scenarios discussed below are summarized in Table 5 (details are provided in Greene et al., 2003).

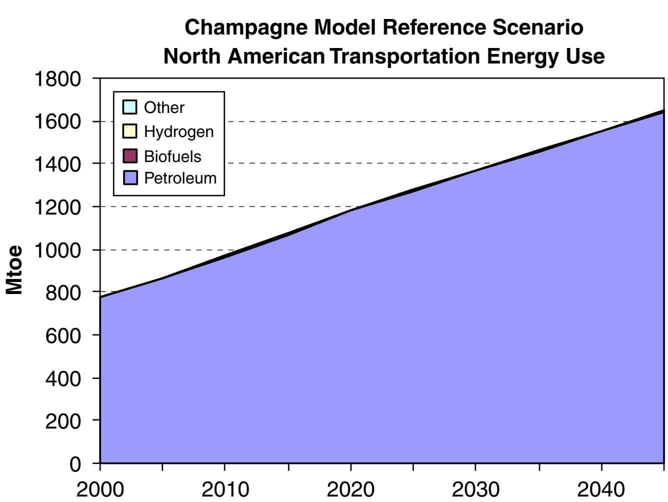

Fig. 5. Champagne model reference scenario North American transportation energy use.

The patterns of energy production from 2000 to 2050 in the modified scenarios (IIASA/WEC scenarios adjusted to the IEO 2002 projections and, for North America adjusted to Champagne model projections) are shown in Fig. 6a for the reference scenario (IIASA/WEC A1, IEO 2002 Reference Case, Champagne Reference Case). Total world energy production grows from 10.6 Gtoe in 2000 to 25.7 Gtoe by 2050. World oil production increases from 3.95 Gtoe in 2000 to 9.48 Gtoe in 2050.

The growth of oil consumption across regions is shown in Fig. 6b. Increases in the OECD outside of the US and Canada are modest (1.1%/yr.), while in the developing world oil use increases at 2.6%/yr, for an overall world growth rate of 1.9%/yr.

Both energy and oil use are much lower in the scenario based on IIASA/WEC's ecologically driven C1 scenario. Global energy production increases at an average annual rate of 0.8% over the 50-year period, from 10.7 Gtoe in 2000 to 15.9 Gtoe in 2050 (Figs. 7a and b). During the last 20 years, the average annual growth rate is only 0.14%. Reflecting the ecological theme of this scenario, coal and oil use initially increase gradually, then steadily decline after 2020. World oil production in 2050 is only 0.3 Gtoe higher than in 2000.

Uncertainties about the quantity of oil remaining to be developed, future oil demand, rates of technological progress and other factors imply that there should also be uncertainty about the timing of the peaking of conventional oil production and the rate of transition to unconventional resources. Given a single set of values for all parameters, the depletion model will calculate paths of conventional and unconventional oil production and depletion for each of the 12 regions. Methods of risk analysis allow key parameter values, about which there is substantial uncertainty, to be specified as probability distributions rather than single point estimates. Risk analysis software executes the model thousands of times, each time drawing a random sample of parameter values from the specified probability distributions. This simulation process produces a frequency distribution rather than single point estimates of selected output variables. In this study, distributions are calculated for the years in which world conventional oil production peaks and the year in

Table 5
Descriptions of three world oil transition scenarios

Scenario acronym	IIASA/WEC global energy scenario	IEO 2002 projection to 2020	Champagne model projection	Conventional oil resource estimate source	Unconventional resource estimate
ARRU (1)	A1	Reference	Reference	USGS	USGS/WEC/IEA
ARRC (2)	A1	Reference	Reference	Campbell	Campbell
CLGU (3)	C1	Low growth	Go your own way	USGS	USGS/WEC/IEA

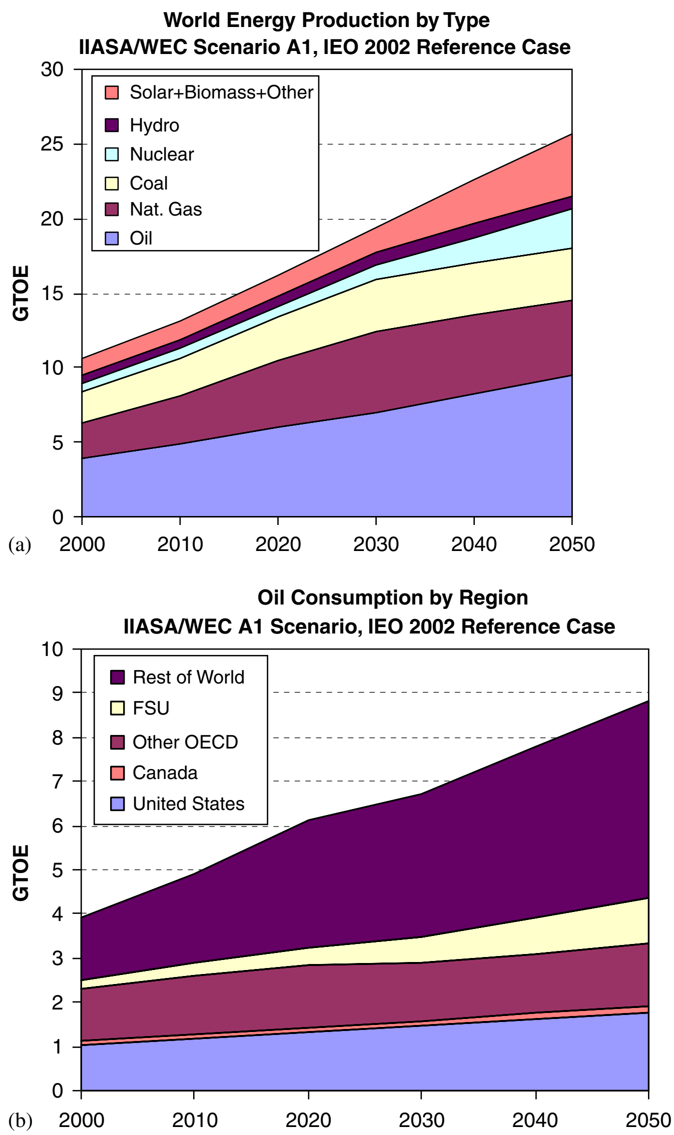

Fig. 6. (a) World energy production by Type IIASA/WEC scenario A1, IEO 2002 reference case, (b) oil consumption by Region IIASA/WEC A1 scenario, IEO 2002 reference case.

which oil production outside of the Middle East and Northern Africa peaks.

The simulation procedure produces a database of outcomes and parameter assumptions that can be analyzed to determine which parameters have the greatest impact on the output variables. Stepwise regression is used to determine which parameters significantly influence the year in which oil production will peak, and to estimate the impacts of each significant determinant.

The assumed ranges for fifteen key parameters are shown in Table 6. In the absence of information about the form of the distributions of these parameters, the uniform distribution was chosen because it is the simplest and reflects maximum uncertainty. It gives greater weight to extreme values than most other distribution functions and will therefore produce greater variance in the peaking date distributions.

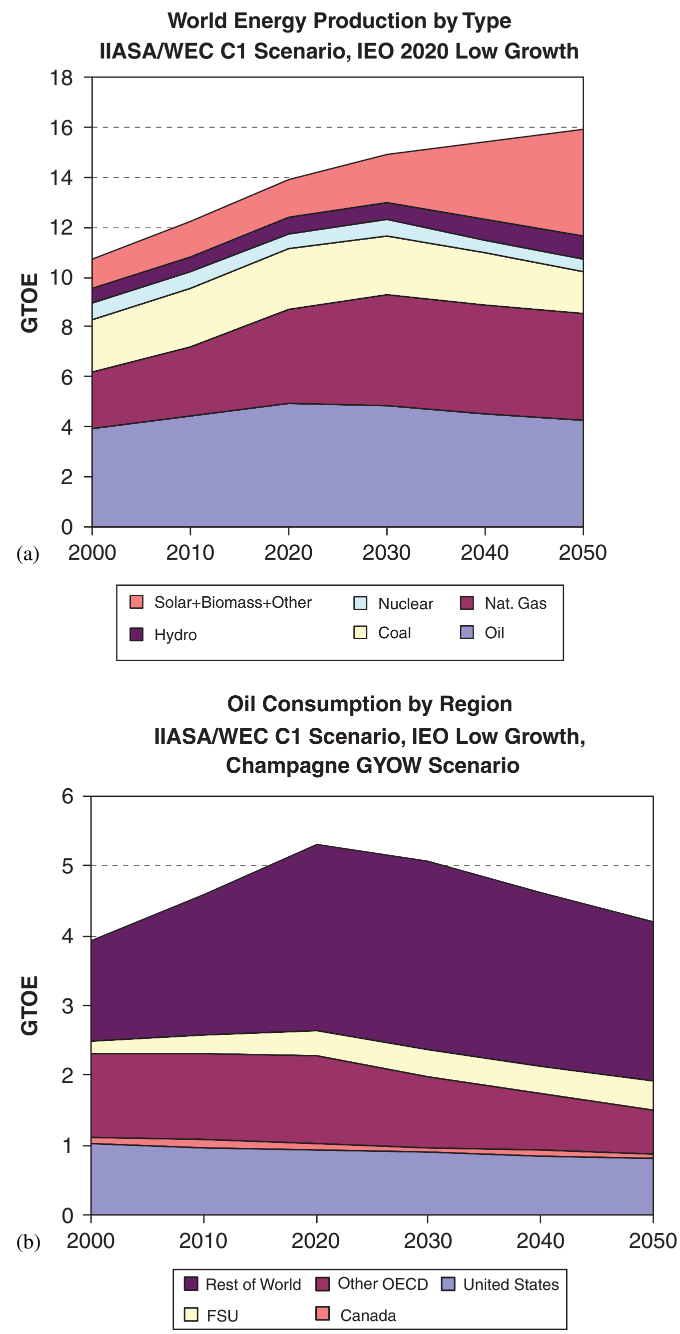

Fig. 7. (a) World energy production by Type IIASA/WEC C1 scenario, IEO 2020 low growth, (b) oil consumption by Region IIASA/WEC C1 scenario, IEO low growth, champagne GYOW scenario.

9. Growth rate of Middle East production

Because Middle East conventional oil production is assumed to be exogenous it too is assigned a probability distribution. In the ‘‘ecological’’ scenario adjusted to the IEO 2002 low economic growth projection, Middle East oil production grows at an average annual rate of 1.5%/yr. from 2000 to 2050. In the A1 scenario adjusted to the IEO 2002 Reference projection, Middle East production increases at an average annual rate of 2.4%. Analyzing the most profitable strategies for OPEC over the next 20 years,

Table 6
Distribution parameters for depletion/transition risk analysis

Parameter	Uniform distribution parameters	
	USGS	Campbell
Growth rate of middle east production		
A1 high growth scenarios	(0.01, 0.02)	(0.01, 0.04)
C1 low growth scenarios	(−0.01, 0.01)	—
Technological change affecting cost[a]		
Conventional oil	(−0.006, −0.002)	(−0.006, −0.002)
Heavy oil & bitumen	(−0.01, −0.004)	(−0.01, −0.004)
Shale oil	(−0.015, −0.005)	(−0.015, −0.005)
Base prices		
Conventional oil	$20/bbl	$20/bbl
Heavy oil & bitumen	($15, $25)	($15, $25)
Shale oil	($40, $90)	($40, $90)
Recovery/reserve expansion	(0.002, 0.008)	(0.002, 0.008)
Speculative resources parameters		
Fraction available	(0.05,0.95)	N.A.
Year of peak conversion	(2015, 2025)	N.A.
Target R/P ratio	(10, 20)	(10, 20)
α (unconv. resource to unconv. reserve conversion rate parameter)	(−150, −50)	(−150, −50)
Supply and demand parameters		
Short run demand elasticity	(−0.08, −0.04)	(−0.08, −0.04)
Short run supply elasticity	(0.04, 0.08)	(0.04, 0.08)
Adjustment rate	(0.85, 0.95)	(0.85, 0.95)

[a]Technological change parameters are assumed to be correlated 0.5.

Gately (2002) concludes that OPEC is not likely to expand output over a long period at a faster rate than 2%/yr. Historically, production from the Persian Gulf region (in the absence of OPEC's influence) increased at an average annual rate of 11% from 1960 to 1973. But since the first oil price shock in 1973 Persian Gulf oil output has actually declined. The average annual rate of decline is −0.5%/yr. but the path has been anything but smooth. Simulations based on the USGS (2000) data show that if the Middle East Region increases production at a rate much greater than 2% per year, its production will become resource-constrained before 2050 (that is, a target R/P of 15 will become constraining). Thus, a uniform probability distribution over the range 1–2%/yr is used when the USGS resource estimates are used. Because ROW production peaks much earlier when Campbell's estimates are used, a wider range of 1–4% is used with his resource estimates. This also results in an early peaking of MEA oil production, a topic that has been addressed by Bakhtiari (2003), e.g., using similar data.

The model allows a technology-driven rate of reduction in the costs of oil production to offset the depletion-driven tendency for increased costs. It is assumed that costs for shale oil production will decrease faster (−0.5%/yr. to −1.5%/yr.) than costs for oil sands production (-0.4%/yr. to −1.0%/yr.) and that costs of conventional oil production will decrease at the slowest rate (−0.2%/yr. to −0.6%/yr.). Generally speaking, with the exception of unconventional oil costs, these rates are not sufficient to offset increases in production costs through 2050 due to the effects of depletion.

In 2000, the long-run *marginal* costs per barrel of producing and delivering the three types of oil are assumed to be: conventional oil $20, oil sands and heavy oil ($15–25), and shale oil ($40–90). This implies that the long-run marginal costs of producing conventional oil (outside of the Middle East) and the median cost of producing oil sands and heavy oil are the same. The state of depletion of conventional oil is far greater, however.

Reserves are assumed to expand due to reserve growth. When the USGS-based resource estimates are used, reserves are assumed to grow at between 0.2% and 0.8%/yr. Reserve growth of 0.5%/yr is about twice the rate observed in the US lower 48 from 1966–1979 (Porter, 1995). A rate of 1%/yr was considered relatively rapid by Davies and Weston (2000). Using the USGS based estimates, a rate of 0.5% is sufficient to transfer nearly all of oil available from reserve growth to producible categories before 2050.

Anywhere from 5% to 95% of speculative resources are made available when USGS estimates are used. Estimates based on Campbell's data do not include speculative resources. Speculative resources are converted to proved reserves at rates determined by a user-specified normal probability density function. The function is determined by specifying the fraction of speculative resources that have already been converted by the year 2000 and the year in which conversion will peak. Here the peak year has been specified as a uniform distribution over the years 2015–2025. In all cases it is assumed that 5% of speculative resources have already been converted to proved reserves by 2000.

Target R/P ratios between 10 and 20 are allowed. If a region's 1995 R/P ratio was below the target ratio, the 1995 R/P value is used instead. For example, for the USGS-based estimates, the US' 1995 R/P ratio was 10.9.

Unconventional resources are converted to unconventional reserves using a logistic function that depends on the R/P ratio for unconventional reserves. As the unconventional R/P ratio nears the target R/P ratio, conversion accelerates. If the actual R/P ratio is 25 and the desired ratio is 20, and α-value of −100 implies that a 1% change in the actual R/P ratio will cause the rate of conversion to increase by about 1%. Values of α range between −150 and −50.

The short-run elasticity of oil demand in all regions is assumed to lie between −0.08 and −0.04. The lagged adjustment parameter is assumed to lie between 0.85 and 0.95, implying a range for the long-run elasticity of −1.6 and −0.3, with a median value of −0.6. Similarly, the short-run elasticity of supply is assumed to lie between 0.04 and 0.08, with a lagged adjustment parameter also between 0.85 and 0.95.

Risk analysis simulations were carried out using the Latin square method of the @Risk® software package (Pallisade Corporation, 2002) for the three scenarios shown in Table 5 using the parameters displayed in Table 6. The first two use the reference world energy scenarios and test the two alternative estimates of world conventional and unconventional oil resources. The last scenario matched the ecologically driven scenario with the USGS-based resource estimates.

10. Results

The results of the risk analysis suggest that whether USGS or Campbell's estimates are used and over a wide range of possible assumptions, the peaking of conventional oil production is a serious and timely issue. Peaking of conventional oil production outside of the Middle East and North Africa appears to be nearly certain before 2030 and, if pessimistic assumptions about oil resources are correct, may have already occurred. Unless Middle Eastern states decided to rapidly expand production to fill the gap that ROW peaking will create, an enormous expansion in unconventional oil production will be required to allow liquid hydrocarbons to fuel the continued growth of global mobility. While it is not impossible that such a transition could be accomplished smoothly, the risk of major supply disruptions, price shocks and economic dislocations must be acknowledged. And even if a smooth transition can be accomplished, a transition to unconventional oil implies greatly increased carbon emissions as well as other environmental challenges. Even in the ecologically driven scenario, there is roughly a 50/50 chance that ROW conventional oil production will peak before world oil demand peaks. Of course, major changes in energy policies around the globe would be required to put the world on this path.

10.1. *Peaking of conventional oil production*

The risk analysis using resource estimates based on the USGS (2000) assessment indicates an expected peak year of about 2023, with a roughly 10% probability that the date could be later than 2028 (Fig. 8). The simulation indicates only a 5% probability that the peak year will occur before 2016, and essentially no chance of non-Middle East conventional oil production peaking before 2010.

In sharp contrast, the simulations based on Campbell's data indicate little chance of the peaking date occurring *after* 2010, and an expected peak production date of 2006 (Fig. 9). Given Campbell's resource estimates, for the quantities of oil required under the Reference case there is simply not enough conventional oil outside of the Middle East to sustain the growth of consumption for more than 10 years. Indeed, Campbell (2003) and Deffeyes (2001) estimate that ROW oil production has already peaked. The estimates presented here differ from Campbell's because Campbell does not include deep water and polar oil as

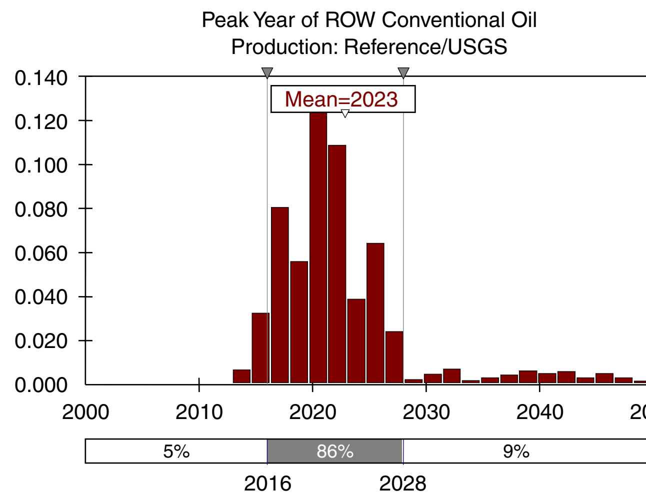

Fig. 8. Peak year of ROW conventional oil production: Reference/USGS.

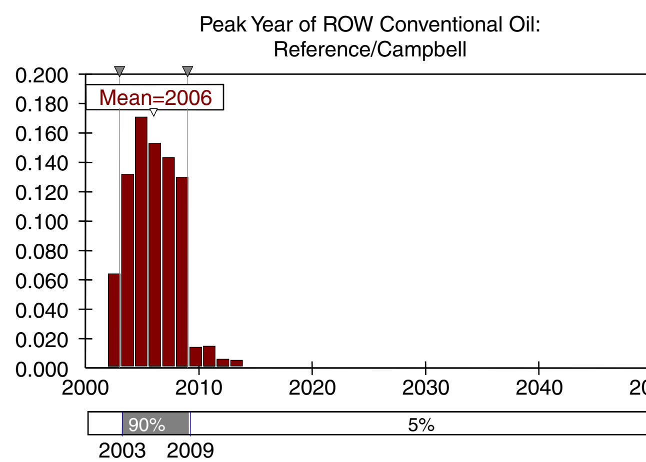

Fig. 9. Peak year of ROW/conventional oil: Reference/Campbell.

conventional, as is done here. Also, this report's assumptions about the factors limiting oil production rates are more optimistic, as has been noted above.

Simulations using the USGS-based resource estimates indicate that the peak year for *world* conventional oil production will be sometime after 2015, but is more likely to occur after 2040 than before (Fig. 10). However, the date of peaking of world oil production depends on how rapidly Middle East producers are willing to expand their output. Because of this, it is very likely that once conventional oil production outside of the Middle East peaks, world oil production will be relatively flat, and marginal supply will need to come from unconventional oil if demand is to grow. Simulations using resource estimates based on Campbell point to 2015 as the expected date of peak world conventional oil production (Fig. 11).

10.2. *Sensitivity analysis of peaking dates*

For analyses using the USGS estimates, the fraction of speculative conventional oil resources assumed to exist is

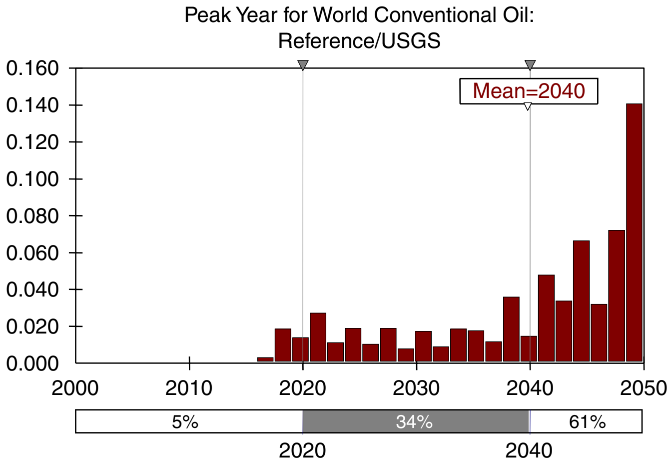

Fig. 10. Peak year for world conventional oil: Reference/USGS.

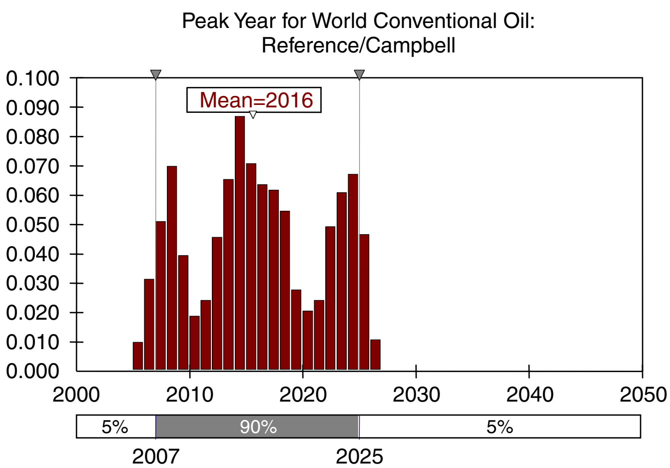

Fig. 11. Peak year for world conventional oil: Reference/Campbell.

the most important determinant of the peaking date for ROW oil production This result quantifies the obvious fact that, all else equal, the more oil there is the later the date of peaking will be. For the analysis of USGS-based estimates, two technical (α) parameters that control how quickly unconventional oil resources can be converted to unconventional reserves are also important. "α pass 1" controls the rate of conversion on the first pass through the Resource Accounting model, "α pass 2" controls on the second and final pass. The two effects are opposite in sign and nearly equal in magnitude, indicating that these parameters may increase the variance of the peak year distribution but have little impact on the central tendency. The date at which the conversion of speculative resources to proved reserves peaks is also significant, indicating that the timing of development of speculative resources also matters, but not as much as the quantity.

The peak year for world conventional oil production exhibits quite a different pattern of sensitivity to parameter values. For the risk analysis using USGS-based estimates, the most important factor overall is the rate of increase in production from the Middle East and Northern Africa. This parameter also has the obvious effect: the faster the Middle East increases production, the later world oil production peaks. In effect, the world oil production peaks when Middle Eastern producers choose for it to peak. The target R/P ratio for non-Middle Eastern producers is the second most important factor. This factor's effect is less direct. The higher the target R/P ratio, the sooner ROW oil production peaks but the flatter the peak is. Since the world peak is largely determined by Middle East output, a long flat ROW production curve postpones the overall world peak. Next in importance are the key determinants of the quantity of conventional oil remaining to be developed: the fraction of speculative resources that will be found and the reserve growth/enhanced recovery rate.

The peaking dates of ROW and world oil production are less sensitive to parameter assumptions when resource data based on Campbell's assessment are used. The world peaking date, for example, depends strongly on only one factor: the rate of increase in Middle East production.

It is important to bear in mind that these estimates incorporate no political or environmental constraints on oil resource use. For example, there are no restrictions on drilling off shore or in the US Arctic National Wildlife Refuge. In addition, on average half the difference between the USGS' 50th and 5th percentile estimates of undiscovered oil is assumed to exist. Finally, no attempt has been made to reflect geologic constraints on the rates of production, such as would be predicted by a Hubbertian analysis. In this sense, the peaking date analysis just described is optimistic.

10.3. Ecologically driven scenario

In the ecologically driven scenario's risk analysis the date of peak conventional oil production outside of the Middle East is sometimes constrained by depletion and sometimes by the peaking of world oil *demand*. Simulations using the USGS-based estimates indicate virtual certainty of ROW peaking between 2010 and 2020 (Fig. 12). Peaking generally does not occur after 2020 because 2020 is the peak year for world oil *demand*. The probability density spike at 2020 roughly indicates what fraction of the time the peaking is demand versus supply constrained. A very small probability of ROW production peaking after 2020 is possible, however, when the growth of Middle East production is negative.

10.4. Transitions to unconventional oil

The risk analysis distributions presented above provide little insight about the paths oil production may take in the course of a transition to unconventional oil. By examining individual cases, one can get a better picture of how oil production and resource depletion might evolve over time.

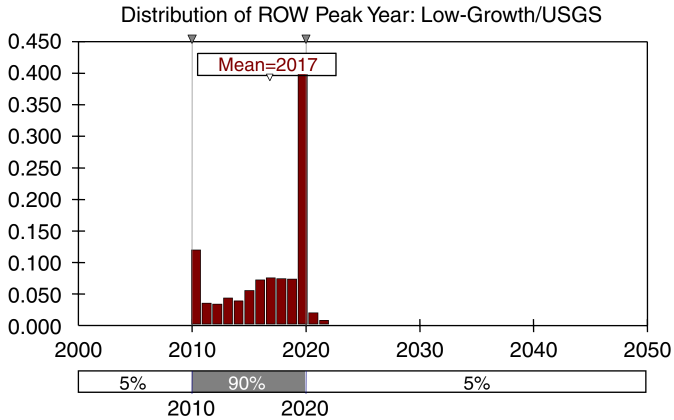

Fig. 12. Distribution of ROW peak year: Low-growth/USGS.

10.4.1. The reference scenario at median parameter values

Using the reference scenarios, USGS-based resource estimates, and assuming the median values for all parameters, total world oil consumption, conventional plus unconventional, increases from 4.0 Gtoe in 2000 to 9.5 Gtoe in 2050. Conventional oil production outside the Middle East (ROW) peaks in 2020 at 3.6 Gtoe (Fig. 13). The decline in ROW oil production after the peak is relatively slow, about −0.75%/yr. over the next 20 years. Duncan (2003) reports that of 24 nations whose oil production has already peaked, the average rate of decline in output has been only −0.23%/yr. Of course, the rate of decline in ROW production will be affected by the rate of increase in Middle East production, which averages +1.5%/yr. in the scenario illustrated by Fig. 13. If Middle East output is assumed to remain constant, the post-peak rate of decline in ROW output goes to −0.45%/yr.

World conventional oil production initially peaks at about the same time, declines slightly and then recovers, finally peaking again in 2048. This peaking date is largely misleading, since oil production is essentially flat after 2020. Since the path of Middle East production is assumed (increasing at 1.5%/yr.) the path of world output is determined by the ROW path and the assumed rate of increase in Middle Eastern production. Middle Eastern producers could, if they so chose, increase production at a faster rate, thereby postponing the initial peak.

World proved reserves of conventional oil peak in 2022, just 2 years *later* than the peak of ROW production of conventional oil (Fig. 14). By that time, the majority of other potential sources of conventional oil (estimated additional reserves, enhanced recovery/reserve expansion, and speculative resources) have been converted to proved reserves. Unconventional oil reserves begin to increase significantly after conventional oil production peaks. By 2050, the majority of unconventional resources have yet to be converted to reserves.

US oil imports increase very slowly through 2020 (Fig. 15). The model estimates that US conventional production can remain flat and even increase slightly until around 2020, as a result of increasing oil prices (to about

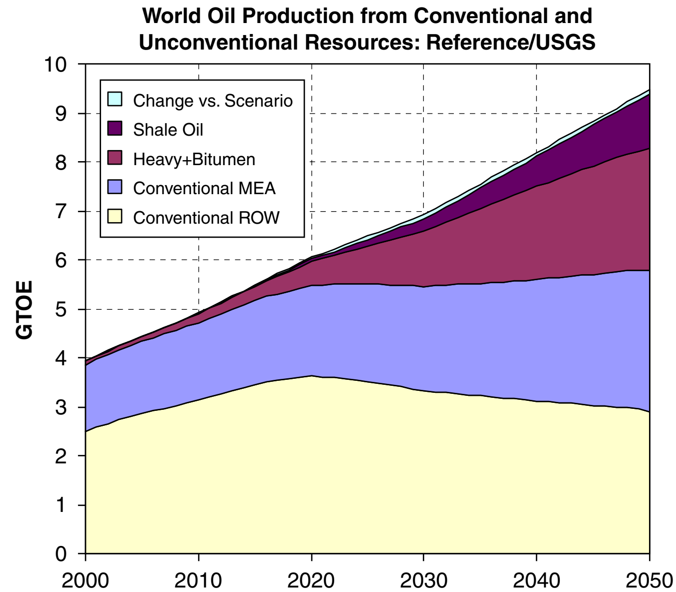

Fig. 13. World oil production from conventional and unconventional resources: Reference/USGS.

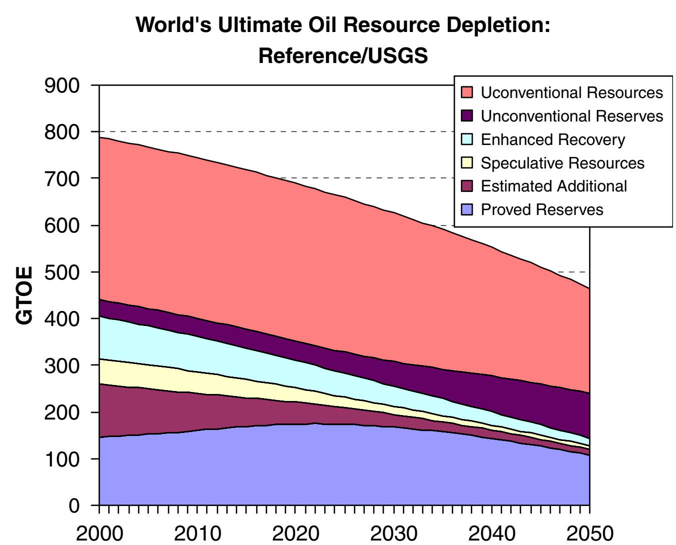

Fig. 14. World's ultimate oil resource depletion: Reference/USGS.

$30/bbl) and contributions from other sources such as ANWR. After 2021, however, production falls off sharply. Initially the gap is filled primarily by increased imports. Eventually US shale oil production, which begins very gradually after 2010, increases rapidly after 2030 and begins cutting into US oil imports after 2040.

The pattern of US production must be considered optimistic, given that it is well known that US production peaked in 1970. Three points are worth making in this regard. First, this is not intended to be a prediction of what will happen. Instead, it is a consequence of the data and assumptions that have been made in this analysis. The key assumption is that production can increase until the target R/P ratio has been reached. Second, no resources are "out

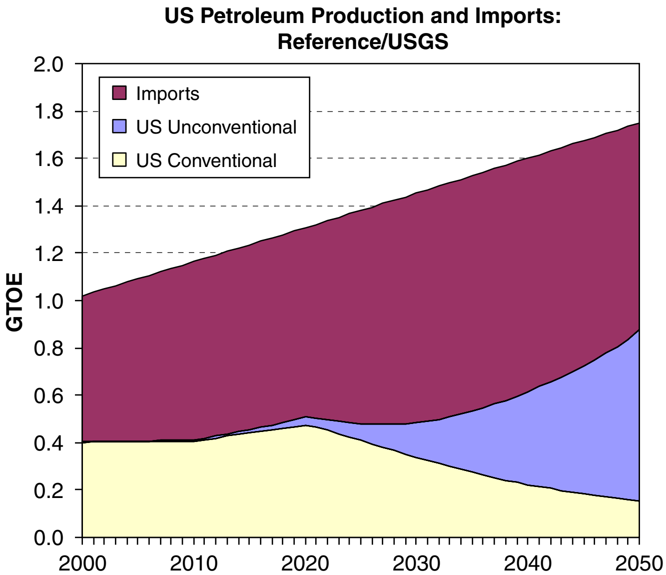

Fig. 15. US petroleum productions and imports: Reference/USGS.

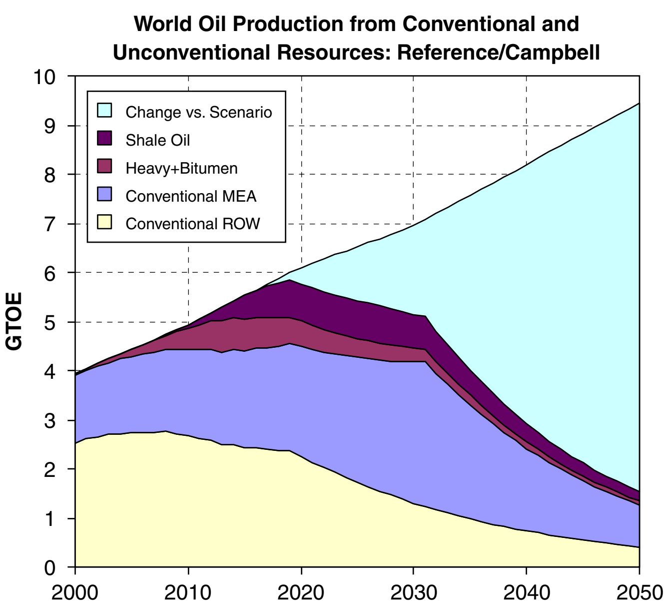

Fig. 16. World oil production from conventional and unconventional resources: Reference/Campbell.

of bounds'' in this analysis, whereas in reality resources may be barred from production for environmental or other reasons. Third, assumptions about the existence of speculative resources, rates of reserve expansion and technological progress affect the rate of oil production in this analysis, and may or may not be too optimistic. These assumptions hold not just for the US but for all regions.

An entirely different picture appears when the resource estimates based on Campbell's data are used. Not only does ROW production peak much earlier in 2008, but the peak in world production of conventional oil in 2019 is swiftly followed by a peak in total production of conventional and unconventional oil in 2020 (Fig. 16). After that, things fall apart. An enormous gap opens up

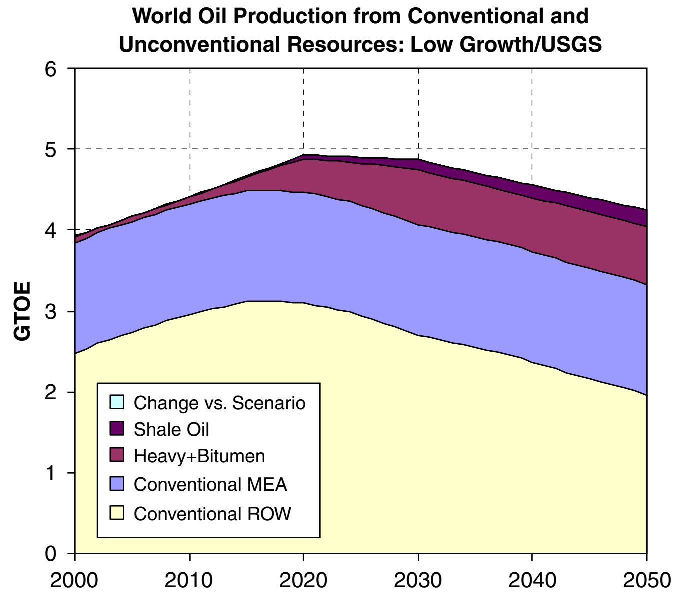

Fig. 17. World oil production from conventional and unconventional resources: Low growth/USGS.

between the scenario's planned production and what is feasible, a gap that must be filled by another energy source not included in this analysis, such as coal, or accommodated by reduced consumption.

10.4.2. *The ecologically driven scenario*

In the ecologically driven scenario total oil consumption peaks at just under 5 Gtoe in 2020, flattens out and then declines to just over 4 Gtoe in 2050 (Fig. 17), about half as much as in the reference scenario. The pattern of growth and decline is demand driven. Middle East production is assumed to range between −1% and +1%, implying a median of 0% growth. ROW conventional oil production peaks in 2015 at 3.1 Gtoe. The peak is a combination of the effects of depletion of conventional oil supplies outside of the Middle East and the economics of low oil prices as a result of slow growth in demand and a backstop supply of oil sands and heavy oil that cost little more than conventional oil. Unconventional oil production expands after 2015, even though the Middle East region would be fully capable of supplying additional conventional oil if it had been assumed to do so.

10.4.3. *Potential implications for OPEC'S market share*

The Middle East and North Africa region can be considered a rough approximation of OPEC (Venezuela, Indonesia and Nigeria being the omitted members). Because Middle East production is an assumption, the model has nothing to say about what OPEC *will* do. However, oil depletion and transition may have important implications for what OPEC *could* do. Market share is a key determinant of OPEC's market power, and it is interesting to track the Middle East market share as ROW conventional oil production peaks and unconventional oil supply comes on line.

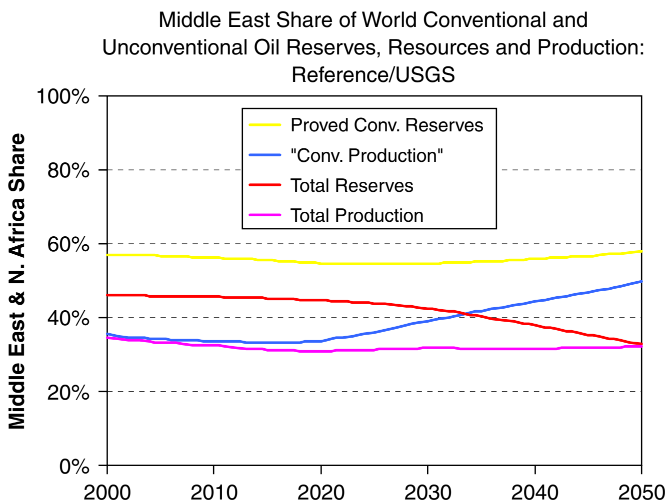

Fig. 18. Middle East share of world conventional and unconventional oil reserves, resources and production: Reference/USGS.

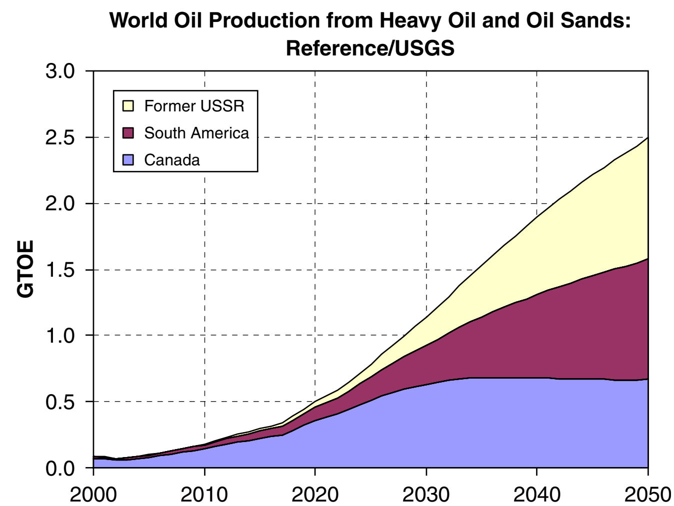

Fig. 19. World oil production from heavy oil and oil sands: Reference/USGS.

Using the reference scenario and the USGS-based resource estimates, if the Middle East region increases output at the modest rate of 1.5%/yr it can maintain about a one-third share of world oil production (conventional and unconventional) through 2050 (Fig. 18). The region's share of conventional production would eventually rise to almost 50% by 2050. Of course, an infinite number of production paths are available for OPEC to choose from. Still, these results suggest that under the Reference scenario and USGS resource estimates, OPEC will be able to maintain a position of dominance in world oil markets for the next 50 years, should it choose to do so, regardless of conventional oil depletion or a transition to unconventional resources.

10.4.4. Where might the unconventional oil come from?

Considering the reference scenario and using the USGS-based resource estimates, oil sands from Canada are the initial major source of unconventional oil supply (Fig. 19). Canadian oil sands production increases rapidly to about 0.7 Gtoe (14 mmbd) after 2030 and then remains nearly flat through 2050. The specific pattern of Canadian supply should not be taken literally since it is not clear whether such a rapid and massive increase in Canadian oil sands production is feasible or desirable. Considering 2030 production targets in the range of 5 mmbd, Canadian government and industry experts foresee major challenges in terms of water availability, on-site upgrading requirements for synthetic oil, energy consumption, environmental impacts and infrastructure needs (ARC, 2003). Additional resources come from Latin America (Venezuela) and the Former Soviet Union (Russia).

Oil shale production begins later, and is driven by continued growth in world oil demand, the peaking of conventional oil supply, limitations on heavy oil and oil sands resources and decreasing costs of shale oil production as a result of technological progress. By 2050 more than 1 Gtoe (20 mmbd) of shale oil is being produced, nearly all of it from the US (Fig. 20). Whether such a rapid expansion and massive production of shale oil would be feasible or acceptable to the US is not considered here, and it is again noted that there may be better alternatives for producing liquid hydrocarbon fuels that have not been included in this analysis.

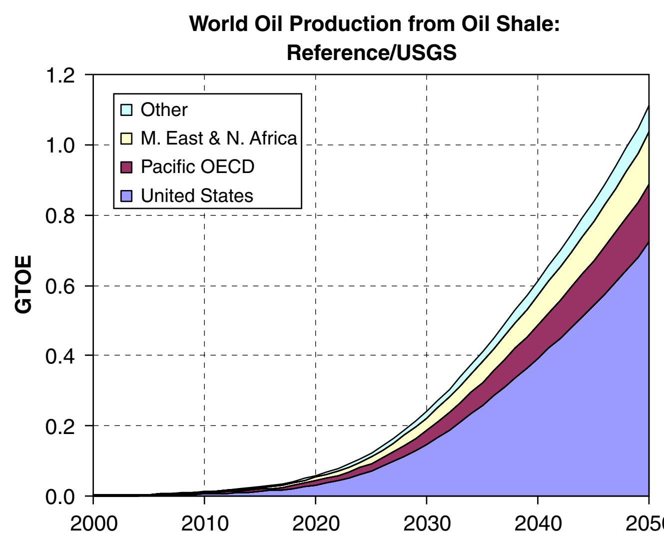

Fig. 20. World oil production from oil shale: Reference/USGS.

11. Conclusions

Peaking of conventional oil production is almost certain to occur soon enough to deserve immediate and serious attention. If peaking is already underway and oil supplies are as limited as the pessimists believe, the world is facing a drastic transition for which it is unprepared. If peaking is one to three decades away, it is not too soon to begin efforts to understand and prepare for the transition to other energy sources. Furthermore, supposing that a smooth transition from conventional to unconventional oil could be achieved, the problems of greatly increased carbon dioxide emissions and continuing oil market dominance by Middle Eastern producers would persist. Even from the optimists perspective, oil peaking is a serious issue.

If present energy use trends continue, unless the best available estimates of world conventional and unconventional resources as well as the representation of uncertainty in these estimates are very seriously in error, a major transition from conventional to unconventional oil will begin before 2030. If the resource estimates based on the USGS (2000) survey are used, peaking of non-Middle Eastern conventional oil production is likely sometime between 2010 and 2030. If the lower resource estimates of Campbell are correct, the transition is already underway. The key determining factors of the date of peak production are how much conventional oil remains and how quickly reserves can expand.

The peaking of conventional oil production is only a part of this equation. Under a wide range of assumptions the rate of growth in world conventional oil production will slow substantially after 2020 if it does not decline. In order for oil consumption to continue to increase at substantial rates, the Middle East region must rapidly expand production or production of oil from unconventional resources must be greatly expanded. Under almost any assumptions, it is not too soon to consider whether this transition is desirable and to evaluate the risks and opportunities it presents.

Assuming the USGS (2000) resource estimates are correct, the transition to unconventional oil will be rapid if the growth of oil consumption continues at current rates or rates projected through 2020 by the Energy Information Administration or the IEA. Rates of growth in unconventional oil supply of 7–9%/yr. appear necessary as the peak in non-Middle East oil production is passed. The transition could be greatly slowed and substantial development of shale oil resources avoided if the growth of world oil consumption could be curbed by 2020, as it is in the ecologically driven scenario. If the pessimistic assessment of world unconventional resources proves to be correct, the transition to unconventional oil will be rapid but limited and short lived, and largely ineffective in preventing a supply constrained downturn in oil consumption.

At first, unconventional oil supplies are likely to come from the oil sands resources of Canada, followed by increased development of Venezuelan and Russian unconventional resources. If growth in demand continues, US shale oil will begin to be developed at a rapid pace following the peaking of conventional oil production from regions outside of the Middle East. Development of oil shale could be delayed by a substantial increase in conventional oil production from the Middle East. Nearly all of the supply of shale oil is likely to come from the US due to its massive shale oil resources. Fossil alternatives to shale oil, such as coal, exist but have not been included in this study.

Given the USGS resource estimates, it appears that the market dominance of MEA oil producers is robust to a wide range of alternative demand and resource availability scenarios. This is evidenced by their ability to maintain market shares in the vicinity of 30 percent to 50 percent over all or most of the 50-year period in all scenarios and variants. Moreover, the Middle East will remain the lowest cost supplier of oil. While the emergence of large-scale unconventional oil production could put a cap on long-run oil prices, with the majority of the world's proved conventional reserves Middle East producers will have the ability to temporarily raise or lower world oil prices throughout the period.

In the reference scenario, US oil imports increase until shale oil (or perhaps coal) becomes an important resource. This is not likely to happen until after 2025, if then. If the model's predictions of flat or increasing US oil output for the next decade or more are overly optimistic (as they probably are) the near-term increase in US imports will be greater still. This implies that the US oil dependence problem is a long-run problem, and one that will probably require major changes in transportation technology, or energy sources for transportation, or both.

The analysis of world oil depletion presented in this paper is dependent on a number of critical assumptions, nearly all of which are debatable. Furthermore, there are several areas in which improvements to data and methods are needed. Nonetheless, it is hoped that this analysis makes a contribution to a better understanding of the future of conventional and unconventional oil supply. The results presented here strongly suggest that it is not too soon to begin analyzing potential transitions from conventional oil and considering alternatives.

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