Running Out of and Into Oil: Analyzing Global Oil Depletion and Transition Through 2050

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ABSTRACT

This paper presents a risk analysis of the peaking of world conventional oil production and the likely transition to unconventional oil resources such as oil sands, heavy oil and shale oil. Estimates of world oil resources by the USGS, the IIASA, the WEC and Dr. C. Campbell provide alternative views of ultimate world oil resources. Global energy scenarios created by IIASA and WEC provide the context for the risk analysis. A model of oil resource depletion and expansion for twelve world regions is combined with a market equilibrium model of conventional and unconventional oil supply and demand. The model does not make use of Hubbert curves. Key variables such as the quantity of undiscovered oil and rates of technological progress are treated as probability distributions, rather than constants. Analyses based on the USGS and IIASA resource assessments indicate that conventional oil production outside the Middle East is likely to peak sometime between 2010 and 2030. Even if oil production does not peak before 2020, output of conventional oil is likely to increase at a substantially slower rate. Analysis based on data produced by Campbell indicates that the peak of non-Middle East production will occur before 2010. Once world conventional oil production peaks, first oil sands and heavy oil from Canada, Venezuela and Russia, and later shale oil from the United States must expand rapidly if total world oil consumption is to continue to increase.

INTRODUCTION

Hubbert's (*1*) strikingly accurate prediction of the peak of U.S. oil output is a powerful reminder that conventional oil resources are indeed finite. On the other hand, oil resources are not a fixed quantity, but a variable that depends on economics, the status of earth science and technology (*2*). Technological change can expand the base of exploitable hydrocarbon occurrences or lead to new systems of energy use that prefer other energy sources to oil (e.g., *3*). Yet, to assume that whatever advances are needed will occur, and at the rates needed to assure continued plentiful supplies of low-cost oil is a matter of faith not science (*4*). The question of whether the availability of oil resources will someday soon prevent us from producing the quantities of oil necessary to power an increasingly mobile world economy seems to be neither a foregone conclusion nor an irrelevancy.

As knowledge of the earth's crust increases, the comprehensiveness and precision with which hydrocarbon occurrences can be characterized increases. Evidence of this is the fact that most estimates of ultimately recoverable resources of conventional oil have remained in the vicinity of 2 trillion barrels over the past four decades (*5, 6*; also Figure 1 from *7*). The most recent estimates by the U.S. Geological Survey (*8*) seem to be an exception to this rule, but the apparent disagreement is largely attributable to a change in definitions. The USGS 2000 estimates include, for the first time, an estimate of the potential for reserve growth due to advances in technology and knowledge of deposits. The estimated 600 billion barrels in this category accounts for nearly all of the difference between the USGS' 1994 (*9*) and 2000 mean estimates.

Before a peak in oil production is reached, the world might begin a transition to an alternative source of energy, thereby permitting energy use to continue to grow. Such a transition would be especially critical for the world's transportation systems that rely almost entirely on petroleum fuels. The most likely, but not only alternatives to conventional oil are unconventional oil and other fossil hydrocarbon resources that can be converted to conventional liquid fuels. The world's resources of shale oil and coal, in particular, are vast and can be converted to conventional hydrocarbon fuels at greater cost and with potentially greater damage to the environment. Other alternatives, such as hydrogen and biomass fuels need further technological development and will require coordinated planning and policy intervention in order to displace conventional fuels. In this paper, it is assumed that the transition will be to unconventional sources of oil: oil and tar sands, heavy oil and shale oil. However, it is readily acknowledged that natural gas and coal could be more economical sources of liquid hydrocarbons than shale oil and that it is the goal of U.S. energy policy to make a transition to hydrogen produced substantially from renewable energy sources. These options are not considered here in order to reduce the complexity of the analysis.

Several recent studies have considered the timing of the peaking of conventional oil production (e.g., *10, 11, 12, 13, 14, 15, 16*). With the exception of Wood et al. (*10*), each study relies on a single scenario of world oil demand growth and one or two estimates of total world oil resources. Wood constructed 12 peaking scenarios based on alternative rates of growth in world oil demand and the USGS's 5%, 95% and mean estimates of ultimate conventional oil resources producing a wide range of peaking dates between 2021 and 2112 (Figure 2). All of Wood's scenarios suggest catastrophically rapid transitions once conventional oil production peaks. Cavallo (*13*) based his estimates on a single scenario of resources and demand, but varied the ratio of resources (proved + undiscovered) to production at which production must begin to decrease between 10 and 15, thereby generating a range of dates for the peaking of non-OPEC production between 2015 and 2020. Manne (*17*) assumed the USGS 2000 5% probability case as a reference which produced an estimate of 2040 for the peak in world oil production. A low resource case assuming only 50% of the undiscovered resources of his reference case produced a peak in 2020. This study extends the "what if" parametric approach of Wood et al. (*10*) by creating an integrated model of the depletion of conventional oil and the transition to unconventional oil resources in a systematic framework. This permits a risk analysis by assuming probability distributions for key parameters affecting: (1) the quantity of conventional oil resources available, (2) rates of technological progress, (3) oil production by Middle Eastern producers, and (4) other economic assumptions. It is important to note that the method used here does not explicitly represent geological constraints on oil production, except for the limitations on quantities of different kinds of resources. In the spirit of "what if" analysis, the analyst is free to specify, for example, rates of technological progress and rates at which production costs will increase with depletion. In this sense, the authors believe it is fair to characterize this study as having an optimistic bias.

The model can also be run using alternative scenarios of world oil demand. It is described briefly in Section 3 and in detail in Greene et al. (*18*).

The threat of global climate change gives reason to be concerned about a transition from conventional to unconventional oil resources. As Grubb (*5*) and others have pointed out, the longer-term problem of climate change depends on the world's decision to burn or not to burn unconventional oil, gas, and coal and release the carbon to the atmosphere.

A global transition to unconventional oil could also shift the balance of power in world oil markets. This study's results indicate that it is very likely that production of conventional oil from countries outside of the Middle East region will peak, or that the rate of increase in production will become highly constrained before 2030. Middle East producers appear to be able to maintain market dominance through that period and beyond if world oil demand continues to grow.

WORLD OIL RESOURCE ESTIMATES

What is Oil?

In any assessment of world oil resources, the first question to be answered is, "What is oil?" (*19*). In this report, 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. In this report, oil available via enhanced recovery is also considered conventional oil. Conventional oil resources are also defined here to include natural gas liquids (NGLs), since a large fraction of these liquids end up being consumed as petroleum products (even though the production of NGL depends on the production of natural gas, not oil, *6*). Unconventional oil comprises deposits of greater density than water (e.g., heavy oil), viscosities in excess of 10,000 cP (e.g., oil sands), or occurrences in tight formations (e.g., shale oil). Recently, some have argued that Canada's oil sands should be classified as conventional oil, while others argue that because of the cost and complexity of operations, water scarcity and other factors Canadian oil sands should remain unconventional (*20*). As Adelman (*21*) notes, fifty years ago offshore crude oil was considered an unconventional resource. From this perspective, what is called here a transition to unconventional fossil resources might alternatively be viewed as a technologically and economically driven redefinition of the resource base for liquid hydrocarbon fuels.

Rogner (*22*) developed a useful framework for organizing and accounting for oil resource data by type of resource and region of the world. Eight categories of resources are distinguished. Category I corresponds to proved recoverable reserves of conventional oil. Category II includes conventional oil occurrences that have not been discovered, but have a "reasonable probability of being discovered." These are comparable to the USGS 50th percentile undiscovered resource estimates. Category III represents more speculative occurrences of conventional oil, and according to Rogner, "…reflects the difference between Masters et al.'s 5% and 50% probability estimates of undiscovered oil and gas occurrences." (*22*, p. 8). This same approach can be applied to the USGS 2000 estimates. Category IV represents the potential for enhanced recovery. Historically, only about 34% of in situ oil has been recovered. Rogner assumes that in the future this will increase to 40%, and notes that this assumption has already been incorporated in his estimates of Category I-III resources. Category IV represents further improvements in recovery rates beyond 40%. The closest USGS category is reserve growth, but the definitions do not match exactly. Reserve growth is intended to combine the effects of technological improvements in recovery rates and the tendency for initial proved reserve estimates to understate the quantity of oil ultimately recoverable from a field. The USGS has acknowledged that its estimates of reserve growth, especially outside of the United States, are highly uncertain. Others argue that apparent reserve growth is an artifact of the way proved reserves are reported for legal and business purposes and that geologists' estimates of the size of a given resource are generally unbiased (e.g., *6*).

Rogner's Category V comprises identified reserves of unconventional oil that can be produced today, or in the near future at current market prices. This includes occurrences of oil sands in Canada and heavy oil in Venezuela. All other unconventional resources were estimated *in toto*, and then allocated by Rogner 20:35:45 percent among categories VI, VII and VIII. Also, all oil remaining after commercial

production via enhanced recovery was added to category VIII. Given that oil shale accounts for the majority of the unconventional resource estimates, and that the vast majority of oil shale occurrences are very low grade (<0.1 ton of oil per ton of shale oil), only Category VI is included in this assessment of unconventional resources through 2050 (Table 1). This assumption is intended to exclude low-grade shale oil and all oil unrecoverable after enhanced recovery.

RESOURCE ESTIMATES USED IN THIS STUDY

In the analyses carried out in this study, three sets of resource estimates are used.

- USGS 2000 (*8*) conventional oil estimates plus unconventional oil estimates synthesized from USGS/WEC/IEA as described below,
- Rogner's (*22*) estimates (Table 2), and
- Estimates based on Campbell's (*23*) year-end 2002 global assessment.

The USGS and Rogner estimates are similar, in part because Rogner made use of an earlier USGS study (*9*) in deriving his estimates of conventional oil resources. The estimates also reflect similar 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 (*23*) is far less sanguine about the ability of technology to expand resources and is more confident about how much oil remains.

The USGS 2000 estimates are available by country, which allowed them to be rearranged into Rogner's 11 world regions (the same regions used by *24*), producing comparable regional estimates. Campbell's global total 2002 estimates were distributed to countries based on each country's share of his own year-end 1999 estimate, which was available by country (*25*). The procedures and data are described in Greene et al. (*18*).

In addition to median estimates, the USGS 2000 study provides mean (expected value) estimates, lower (95th percentile) and upper (5th percentile) confidence intervals on estimates of undiscovered resources and reserve growth. The low estimate of total conventional oil resources is 2.3 trillion barrels, 2.5 trillion including NGLs. The upper estimate including NGLs is 4.4 trillion barrels. The mean estimate for crude oil is 3.0 trillion, for petroleum including NGLs is 3.3 trillion. All these estimates include cumulative production to 2000 of 0.54 trillion barrels (Table 3).

Heavy Oil and Bitumen (Tar or Oil Sands)

Rogner's estimates of unconventional oil resources can be compared with estimates derived from other sources: USGS (*26*), WEC (*27*) and IEA (*28*). Recoverable reserves of bitumen (oil and tar sands) and heavy oil appear to be highly concentrated in three regions: (1) Alberta, Canada, (2) the Orinoco Oil Belt of Venezuela, and (3) Russia. The derivation of the estimates shown in Table 4 can be found in Greene et al. (*18*).

In terms of total unconventional oil resources, the estimates derived from IEA/WEC/USGS estimates compare well with Rogner's estimate of 381 Gtoe of category V and VI resources. A comparison at the regional level, however, reveals considerable disagreement reflecting the higher level of uncertainty about these resources.

The division of unconventional oil resources into oil shale versus heavy oil and oil sands leads to a dichotomy of regions. If one divides the North American region into Canada and the United States, it appears that every region can be described as either oil sands/heavy oil dominant, or oil shale dominant. Only FSU and LAM appear to have significant quantities of both resources, and these two regions are more than 80% oil sands.

MODELING OIL DEPLETION

A World Energy Scenarios Model (WESM) was developed to assess the implications of alternative, long-term, world energy scenarios for the depletion of conventional oil and the likely transition to unconventional oil. The 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 world wide, 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. The details of this model including the equations used are presented in Greene et al. (*18*).

The WESM model was designed to use the world energy scenarios created by the IIASA and the WEC through 2050 (*24*). A IIASA/WEC scenario can also be adjusted to match a U.S. Department of Energy International Energy Outlook 2002 projection to the year 2020 (*29*). Beyond 2020 variables are trended back towards the original IIASA/WEC scenario using splining methods. Every IIASA/WEC scenario for North America foresaw lower rates of growth in oil demand from 1995 to 2000 than were actually experienced. Therefore, for North America, WESM can also be calibrated to detailed transportation energy forecasts developed by the U.S. Department of Energy and Natural Resources Canada using the Champagne Model (*30, 31*).

Resource Accounting

Proved reserves are treated as the stock from which current production is drawn and to which additions are made from other resource categories (*32*). If a scenario's production requirement for a region can be met from the proved reserves of that region, the full amount of the requirement is withdrawn from proved reserves. A region is considered unable to meet a production requirement if the ratio of its proved reserves to the production requirement is below a user specified target (R/P)* ratio. At that point, only R/(R/P)* can be supplied. The rest is set aside as potential demand for unconventional oil. The R/P ratio rule was used by Wood et al. (*10*) and Cavallo (*13*) who defined reserves as the USGS estimates of proved plus undiscovered resources. Cavallo termed this the R_{P+U}/P ratio, and concluded that production in a region would begin to decrease when the ratio was somewhere between 10 and 15.

The "target R/P" approach is not likely to satisfy advocates of the Hubbert theory, who might argue that it will not be possible for regions to continue increasing production, or even hold it constant beyond the 50% depletion point (e.g., *6*). 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., *3*). By adopting the R/P rule, we are allowing the possibility that production might increase beyond the 50% point, in effect adopting the economists' viewpoint. This should not be interpreted as a rejection of the Hubbertian viewpoint, but rather a decision to investigate how depletion and transition might play out under the more optimistic assumption.

Accounting for Conventional Oil Depletion

In WESM, proved reserves are continuously augmented by additions from speculative and estimated additional resources, as well as from reserve expansion. Withdrawals from proved reserves are primarily replenished by flows from *estimated additional* reserves. The inflow from estimated additional reserves is set equal to the current year's production from proved reserves if the ratio of the quantity of estimated additional reserves to the required flow exceeds the target R/P ratio. Otherwise, the flow is set equal to the quantity of estimated additional reserves divided by the target R/P ratio.

Speculative resources, if any are assumed to exist, are added to proved reserves according to a user-specified bell-shaped curve. The user specifies the date at which half of the speculative resources will have been converted to proved resources and the fraction that has already been converted at the start of the forecast. Like other conventional oil resources, speculative resources expand over time due to reserve growth.

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. Estimation of worldwide reserve growth is a new field of analysis and subject to substantial uncertainty. The USGS estimates are based predominantly on historical experience in the United States which, for a number of reasons, might

overestimate the potential for global reserve growth. Reserve growth must be withdrawn from category IV resources, comprising "enhanced recovery" in Rogner's data and "reserves growth" in the USGS 2000 study. As long as there are remaining resources in category IV, reserve growth continues at the specified rate.

The Transition to Unconventional Oil

Just as for conventional oil, proved reserves of unconventional oil are the stock from which all unconventional oil is produced. Additions to proved reserves of unconventional oil, however, are drawn solely from category VI, remaining unconventional resources, using a function that attempts to maintain the target R/P ratio for unconventional reserves. No reserve growth is assumed. Details can be found in Greene et al. (*18*).

A *potential* call on unconventional oil is generated when, in any given year, a region is unable to supply the oil production specified by a scenario from its conventional oil reserves. When this occurs, an oil production deficit is created for that region in that year. Conventional oil production deficits are summed over all regions to obtain a global conventional oil production deficit. Initially, the entire deficit is allocated to unconventional oil and shared to regions according to each region's share of unconventional recoverable reserves. The final division between conventional and unconventional oil, as well as each region's output, is determined in the oil market model, based on supply costs. If world resources of even unconventional oil are inadequate the price of oil will rise until supply equals demand. At present the model includes no "backstop" energy source beyond unconventional oil, though in reality liquid fuels could be made from coal, natural gas or biomass. As will be seen below, this becomes a serious constraint in model runs using resource estimates based on Campbell (*23*).

World Oil Market Model: Long-run Dynamics

The purpose of simulating world oil market dynamics is not to predict future oil prices or to change a scenario's patterns of supply and demand. Rather, it is to simulate the transition from conventional to unconventional oil with sensitivity to the assumed costs of producing the two categories of oil.

Simulating a Transition to Unconventional Oil

In addition to producing an initial estimate of how much of each region's oil supply will come from conventional versus unconventional oil, the resource accounting model also calculates the state of depletion (%) for each region's ultimate resources of conventional and unconventional oil. Logistic depletion/cost curves are used to predict the cost of producing conventional and unconventional oil in each region as a function of the fraction of each region's ultimate resources that have already been consumed. Each cost-quantity pair is assumed to be a point on a regional supply curve. In the World Oil Market model, regional short-run supply curves are calibrated based on these points and: (1) an assumed elasticity of supply, (2) an assumed rate at which supply adjusts to price changes, and (3) last year's production. Given the regional supply curves, it is possible to calculate the world oil market price that exactly satisfies the scenario's total world oil demand. This world oil price plus each region's scenario oil use is assumed to be a point on a region's demand curve. Short-run regional demand curves can then be calibrated given: (1) a user-supplied price elasticity, (2) and assumed adjustment rate, and (3) last year's oil consumption. The World Oil Market model then calculates a market equilibrium solution that determines which regions supply how much conventional and unconventional oil at each year's world oil price.

The Middle East and North Africa (MEA) region, comprised chiefly of OPEC members, is not represented by a supply function. Instead, its production of conventional and unconventional oil are treated as exogenous. The separate treatment of Middle East and rest-of-the-world (ROW) resources is similar to Cavallo's (*13*) method. MEA oil supply is initially set by the scenario but can be changed by the model user. For the risk analysis simulations, the user may supply a probability distribution of annual rates of growth in MEA oil supply.

SCENARIOS OF WORLD ENERGY SUPPLY AND DEMAND

World energy use and supply scenarios were taken from the IIASA/WEC study, *Global Energy Perspectives*, (*24*) and from forecasts of international energy use to 2020 by the U.S. Energy Information

Administration (*29*). Two IIASA/WEC scenarios are used: (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" (*24*, 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.

In both scenarios, world population grows from 5.3 billion in 1990 to 10.1 billion by 2050. Since the IIASA/WEC study in the UN has revised its population projections downward to 8.9 billion in 2050 as a medium estimate and 10.6 as a high estimate (http://esa.un.org/unpp/p2k0data.asp). 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. Largely due to significant declines in the energy intensity of GWP, total world primary energy use increases from 9 Gtoe 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. All but two of the six scenarios examined below are based on the IIASA/WEC A1 scenario.

Because the IIASA/WEC scenarios are already somewhat out of synch with actual year 2000 energy consumption and production, they were adjusted to match U.S. Energy Information Administration Annual Energy Outlook 2002 forecasts to 2020. The A1 scenario most closely resembled the AEO 2002 Reference Case, and so was calibrated to that projection through 2020. The C1 scenario was calibrated to the AEO 2002 "Low Growth" projection. After 2020, a splining method (see *18* for details) was used to trend the projections back towards the appropriate IIASA/WEC scenario.

In the IEO 2002 Reference Case, world energy use increases from 9.6 Gtoe (350 quads, at 40.4 quads/Gtoe) in 1999 to 15.4 Gtoe by 2020 (*29*). 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 (7.8%) in 2020 and then decreases to 879 Mtoe by 2050. In reality, U.S. 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 (*30, 31*) have been substituted for the IIASA/WEC scenarios' North American oil use projections (details are provided in *18*).

In the Reference Scenario, 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 Figure 3. Increases in the OECD outside of the United States 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 fifty-year period, from 10.7 Gtoe in 2000 to 15.9 Gtoe in 2050. During the last 20 years, the average annual growth rate is only 0.14%. World oil production in 2050 is only 0.3 Gtoe higher than in 2000. World oil use peaks in 2020 and declines rapidly thereafter (Figure 4). Given the path of world primary oil use, it is a foregone conclusion that not only conventional but total world oil production will peak by 2020 in this scenario.

Risk Analysis of Oil Peaking and Transition

Risk analyses were conducted for six world energy and oil resource scenarios, as described in Table 5. The six scenarios test the three alternative sets of conventional and unconventional oil resources against a reference world energy scenario, then test somewhat higher and radically lower energy scenarios against the resource estimates based on the USGS 2000 assessment, and finally examine the implications of a pessimistic assessment of world oil resources in the low energy use scenario.

Distributions are calculated for the years in which world conventional oil production peaks, and the year in which oil production outside of the Middle East peaks, as well as the volumes of oil produced at peak production. Given a single set of values for all parameters, the WESM model will calculate paths of conventional and unconventional oil production and depletion for each of the twelve 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 WESM 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.

The probability distributions used for fourteen key parameters are shown in Table 6. Although a wide range of probability distributions could have been used, in every case the parameters are assumed to follow the uniform distribution. In the absence of information about the form of the distributions of these parameters, the uniform distribution was chosen because it is the simplest. However, it gives greater weight to extreme values than most other distribution functions. A discussion of the choices of parameter values can be found in Greene et al. (*18*).

RESULTS

Risk analysis simulations were carried out using the @Risk® software package (*33*).

Peaking of Conventional Oil Production

Given the reference scenario, the distributions of the peak year of conventional oil production from "rest-of-world" (ROW) countries (outside the Middle East) are shown in Figures 5, 6 and 7. The simulation 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 would be later than 2028. The simulation results suggest 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.

The simulations based on Rogner's estimates indicate a wider range of probable peaking dates for ROW conventional oil production, but a very similar expected peaking date: 2025. These results suggest a nearly uniform probability for dates between 2013 and 2037 and, unlike the USGS-based estimates, a substantial probability of peaking after 2030. There appear to be negligible probabilities for peaking dates before 2010 or after 2040.

The simulations based on Campbell's estimates indicate little chance of the ROW peaking date occurring after 2010, and an expected peak production date of 2006. 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.

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. Given the high relative frequency with which the year 2050 occurs, a post-2050 date must also be a possibility. The expected date is approximately 2040, but this estimate is undoubtedly biased downward by the truncation of the analysis at 2050.

Substituting Rogner's resource estimates produces a greater certainty of the conventional oil peak occurring before 2050 but a similar expected peaking data: 2038. These simulations also indicate almost no chance of a world peak occurring before 2015.

On the other hand, the simulations using resource estimates based on Campbell point to 2015 as the expected date of peak world conventional oil production.

Low Growth Scenario

In the Low-Growth scenario the date of peak conventional oil production is partly constrained by depletion and partly by the peaking of world oil demand. The Low-Growth scenario requires a very different assumption about production from the Middle East and Northern Africa. The Reference and High-Growth scenarios assume that Middle East production will increase by from 1-2% per year and even up to 4% per year. In the face of decreasing demand, such rates of growth in oil production would drive world oil prices to absurdly low levels. For this reason, Middle East production is assumed to grow at between –1% and 1% per year in the Low Growth Scenario.

Simulations using the USGS based estimates indicate virtual certainty of ROW peaking between 2010 and 2020. Peaking does not occur after 2020 because 2020 is the peak year for world oil *demand*. A probability density spike at 2020 indicates that peaking is demand driven about 40% of the time.

High Growth Scenario

The High-Growth scenario is calibrated to the IEO 2002 High Economic Growth Projection and additionally assumes that energy intensities will decline at only 0.6%/yr. instead of 0.9%. This causes a greater concentration of probability around the year 2020, but the mean is less than one year sooner than the Reference scenario, and there is still a 5% probability that the peaking date will exceed 2036.

Transitions to Unconventional Oil

The risk analysis distributions presented above provide a useful summary of key output variables but little insight about the paths oil production may take in the course of a transition to unconventional oil. By examining certain individual cases, one can get a better picture of how oil production and resource depletion are evolving over time. In this section, results are presented for the median values of parameters for five of the six scenarios.

The Reference Scenario at Median Parameter Values

Using the Reference scenarios and USGS based resource estimates, 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 (Figure 8). The decline in ROW oil production after the peak is relatively slow, about -0.75%/yr. over the next 20 years. Duncan (*14*) 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 Figure 8. If Middle East output is assumed to remain constant, the post-peak rate of decline in ROW output is only –0.45%/yr.

U.S. oil imports increase very slowly through 2020 (Figure 9). The WESM model estimates that U.S. conventional production can remain flat and even increase slightly until around 2020, as a result of increasing oil prices (to about $30/bbl) and contributions to proved reserves from other sources. In 2021, however, the R/P ratio hits the target value and subsequent production falls off sharply. Initially the gap is filled primarily by increased imports. Eventually U.S. shale oil production, which begins very gradually after 2010, increases rapidly after 2030 and begins cutting into U.S. oil imports after 2040. Shale oil plays the role of a backstop liquid fuel source in this analysis. In reality, coal, natural gas, biomass or efficiency improvements could be used to fill the gap.

The pattern of U.S. production must be considered optimistic, given that U.S. production peaked in 1970. This should not be considered a prediction of what will happen but rather a consequence of the data and assumptions that have been made in this analysis. As such it suggests that the premises of this analysis may be too optimistic. The key relevant assumption is that production can increase until the target R/P ratio has been reached. Hubbertian analysis would probably conclude that this is far too optimistic an assumption. Also, no resources are “out of bounds” in this analysis, whereas in reality resources may be barred from production for environmental or other reasons. Finally, 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 also be too optimistic.

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 (Figure 10). After that, things fall apart. WESM is not currently designed to handle a situation in which even unconventional resources fall far short of a scenario's projections. An enormous gap opens up between the scenario's planned production and what is feasible, a gap that must be filled by another energy source not included in WESM or accommodated by drastic reductions in demand.

Low and High Energy Growth Scenarios

In the Low Growth scenario with USGS based resource estimates total oil consumption peaks at just under 5 Gtoe in 2020, flattens out and then declines to just over 4 Gtoe in 2050 (Figure 11), about half as much as in the Reference scenario. The pattern of growth and decline is demand driven. Middle East production is assumed to remain constant. A faster rate of increase in Middle East production would reduce the quantities of unconventional oil produced.

The High Growth path with USGS based resource estimates leads to 11.5 Gtoe of total oil consumption in 2050. Rest of World conventional oil production peaks in 2020 at 3.87 Gtoe, world conventional oil output peaks in 2041 at 5.95 Gtoe (Figure 12), again largely driven by the assumed rate of growth in Middle East production of 1.5%/yr. In the High Growth case the rate of growth of ROW output begins to slow after 2010 resulting in an earlier increase in the market share of heavy oil and oil sands. By 2020 heavy oil and oil sands production exceeds 1 Gtoe (20 mmbd). From 2010 to 2030, heavy oil and oil sands production grows at 7.9%/yr., while overall unconventional oil production grows at an average annual rate of 8.8%. The implied growth in U.S. shale oil production after 2020 is higher still: it increases from under 0.1 Gtoe in 2020 to 1.35 Gtoe (27 mmbd) in 2050 at an average rate of 9.2%/yr. This is nearly equal to total U.S. 2050 oil consumption in the High Growth Scenario.

Potential Implications for OPEC's Market Share

In the WESM model, 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 WESM 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 WESM can track the Middle East market share as ROW conventional oil production peaks and unconventional oil supply comes on line. Different assumptions about OPEC's production path can be tested in the context of alternative scenarios.

Using the Reference Scenario and the USGS based resource estimates, if the Middle East region increases output at the rate of 1.5% per year it can maintain about a one third share of world oil production (conventional and unconventional) through 2050 (Figure 13). The Middle East's share of proved conventional reserves also would remain constant at just under 60%. The region's share of conventional production would eventually rise to almost 50% by 2050. As the supplier of a large fraction of the world's low-cost oil and owner of most of the low-cost reserves, the Middle East should be able to maintain a dominant position in world oil markets for the next 50 years. By expanding output at a faster rate, the Middle East could gain market share early on, but as a result might encounter the R/P limit before 2050. If the Middle East maintains a steady rate of increase in output of 3%/yr., the region's share of total production (conventional and unconventional) approaches 60% after 2030, but then declines rapidly as the R/P limit is reached. Of course, it is not necessary for OPEC to maintain a constant rate of expansion in production and an infinite number of production paths are available to choose from. Still, these results suggest that OPEC will be able to maintain a position of dominance in world oil for the next 50 years, should it choose to do so, regardless of conventional oil depletion or a transition to unconventional resources.

Where Might the Unconventional Oil Come From?

Because of the very large uncertainties about the costs and quantities of unconventional oil resources, WESM's predictions of where unconventional oil will come from should be considered very uncertain. They reflect the influence of two factors: (1) the type of unconventional oil a region possesses, and (2) the quantity it is estimated to hold.

Considering the Reference Scenario and using the USGS based resource estimates, oil sands from Canada are the initial major source of unconventional oil supply (Figure 14). 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 too seriously since it partly depends on the initial allocation of oil sands resources between reserves and resources, an issue that is in a state of flux even today. It is also not clear whether such an expansion of Canadian oil sands production is feasible or desirable. In considering production targets in the range of 5 mmbd for 2030, Canadian government and industry experts foresee substantial challenges in terms of water availability, upgrading requirements, energy consumption, environmental impacts and infrastructure needs (*34*). 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 the rate of increase in heavy oil and oil sands production (only three regions possess these 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 United States (Figure 15). In the High Growth scenario, 2 Gtoe of shale oil are required. Whether such a rapid expansion and massive production of shale oil would be feasible or acceptable, or whether other feedstocks such as coal or natural gas might be more competitive is not considered here.

CONCLUSIONS

The risk analyses of world oil depletion presented in this report are dependent on a number of critical assumptions, nearly all of which are debatable. The authors believe their assumptions and methods are more likely to err on the side of optimism than pessimism. There is considerable room for improvement in both methodology and data.

Is the Peaking of Conventional Oil Production Imminent?

If present energy use trends continue (as represented by the High Growth and Reference scenarios), 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 and possibly other energy sources will begin before 2030. If the resource estimates based on Rogner (*22*) or those based on the USGS 2000 survey are used, peaking of non-Middle Eastern conventional oil production is likely sometime between 2015 and 2030. If the lowest resource estimates are correct, the transition is already underway.

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. The implication is that 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.

Will the Transition be Rapid or Slow?

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. The transition could be greatly slowed and the need for unconventional oil resources reduced if the growth of world oil consumption could be curbed by 2020. 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.

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 of 30% to 50% over the entire 50-year period in all scenarios and variants. Moreover, the Middle East will remain the lowest cost supplier of oil.

In the absence of dramatic efficiency improvements, U.S. oil imports are likely to increase unless and until shale oil, coal, or some other indigenous substitutes become important resources. This is not likely to happen until after 2025, if then. If the WESM models predictions of flat or increasing U.S. oil output for the next decade or more are overly optimistic (as they probably are) the near-term increase in U.S. imports will be greater still.

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TABLE 1 Estimated World Oil Resource Occurrences, in Gigatonnes of Oil Equivalent (Gtoe) (1 Gtoe = 7.33 Billion bbls of oil)

Region	Conventional Oil			Unconventional Oil					Total
	I	II	III	IV	V	VI	VII	VIII	I-VI
North America	8.5	8.6	6.7	15.9	7.6	98.8	172.8	287.4	606
Latin America	17.4	8.9	15.5	18.9	2.6	91.5	160.1	270.8	586
Western Europe	5.6	2.1	3.6	5.1	1.3	7.6	13.3	34.6	73
Central and Eastern Europe	0.3	0.2	0.6	0.7	0.0	0.5	1.0	3.8	7
Former Soviet Union	17.1	13.6	19.3	23.4	3.3	19.4	34.0	125.6	256
Middle East and North Africa	87.9	17.0	21.9	56.2	22.3	39.6	69.3	279.0	593
Sub-Saharan Africa	4.0	3.4	4.9	5.4	1.4	5.1	8.9	29.7	63
China & Centrally Planned Assoc.	5.1	4.7	8.2	7.4	2.3	42.2	73.8	118.7	262
Pacific OECD	0.4	0.3	0.6	0.7	3.7	25.8	45.1	60.3	137
Other Pacific Asia	2.9	1.6	2.5	3.4	0.6	4.8	8.3	23.0	47
South Asia	1.0	0.3	0.6	0.8	0.1	0.3	0.5	3.5	7
WORLD	150	61	84	138	45	336	587	1237	2638

Source: Rogner, 1997, table 4.

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
Know 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

TABLE 3 Estimates of World Petroleum Resources 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

Source*:* USGS 2000, Table AR-1. USGS estimates combine U.S. NGLs with oil but separate the two for the rest of the world estimates. In Table 1, onshore U.S. NGLs have been removed from the USGS oil estimates and included with NGLs. Historical U.S. NGL production was calculated for 1949-2000 and also removed from U.S. oil estimates and added to NGLs. It was not possible to estimate U.S. offshore NGLs resources remaining under any category. These are included with oil.

TABLE 4 Estimates of World Oil Sands and Oil Shale Resources from Three Sources

Region	Based on IEA/WEC/USGS				Rogner V+VI Unconv. (Gtoe)
	Oil Shale (Gtoe)	Heavy Oil & Oil Sands (Gtoe)	Share Heavy Oil & Oil Sands (%)	Total 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.

TABLE 5 Descriptions of Six 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
ARRR (2)	A1	Reference	Reference	Rogner	Rogner
ARRC (3)	A1	Reference	Reference	Campbell	Campbell
AHRU (4)	A1	High Growth	Reference	USGS	USGS/WEC/IEA
CLGU (5)	C1	Low Growth	Go Your Own Way	USGS	USGS/WEC/IEA
CLGC (6)	C1	Low Growth	Go Your Own Way	Campbell	Campbell

TABLE 6 Distribution Parameters for Depletion/Transition Risk Analysis

Parameter	Uniform Distribution Parameters		
	USGS	Rogner	Campbell
Growth rate of Middle East production (per year)			
A1 high growth scenarios	(0.01, 0.02)	(0.01, 0.02)	(0.01, 0.04)
C1 low growth scenarios	(-0.01, 0.01)	—	—
Technological change affecting cost* (per year)			
Conventional oil	(-0.006, -0.002)	(-0.006, -0.002)	(-0.006, -0.002)
Heavy oil & bitumen	(-0.01, -0.004)	(-0.01, -0.004)	(-0.01, -0.004)
Shale oil	(-0.015, -0.005)	(-0.015, -0.005)	(-0.015, -0.005)
Base prices (2000 $ per barrel)			
Conventional oil	$20/bbl	$20/bbl	$20/bbl
Heavy oil & bitumen	($15, $25)	($15, $25)	($15, $25)
Shale oil	($40, $90)	($40, $90)	($40, $90)
Recovery/reserve expansion (per year)	(0.002, 0.008)	(0.005, 0.015)	(0.002, 0.008)
Speculative resources parameters			
Fraction available	(0.05, 0.95)	(0.05, 0.95)	N.A.
Year of peak conversion	(2015, 2025)	(2015, 2025)	N.A.
Target R/P ratio	(10, 20)	(10, 20)	(10, 20)
Supply and demand parameters			
Short run demand elasticity	(-0.08, -0.04)	(-0.08, -0.04)	(-0.08, -0.04)
Short run supply elasticity	(0.04, 0.08)	(0.04, 0.08)	(0.04, 0.08)
Adjustment rate	(0.85, 0.95)	(0.85, 0.95)	(0.85, 0.95)

* Technological change parameters are assumed to be correlated 0.5.

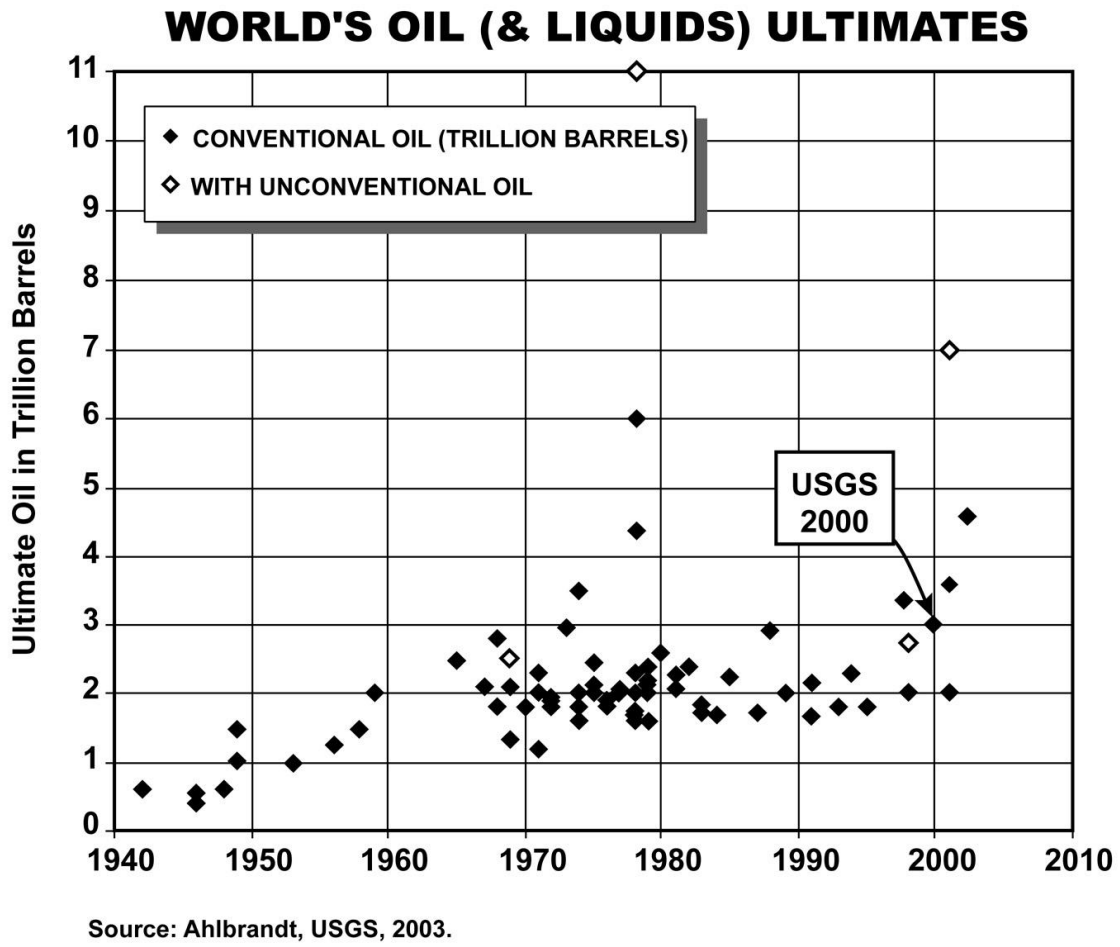
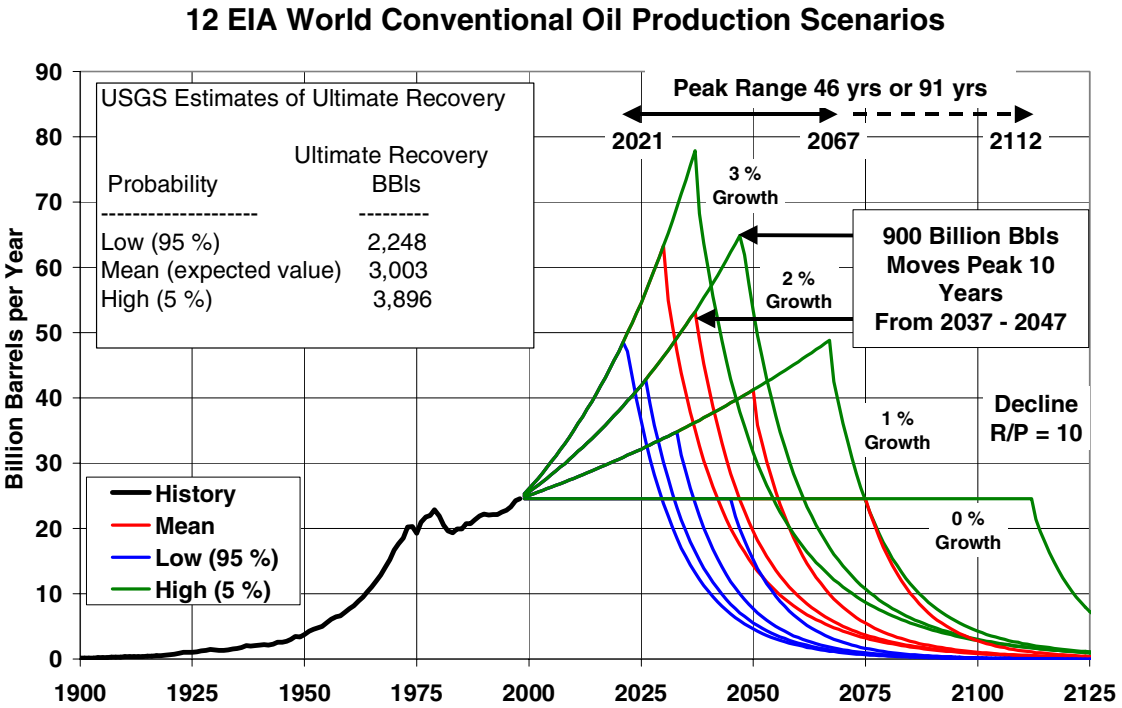


FIGURE 1 World's Oil (& Liquids) and Gas Ultimates.



Note: U.S. volumes were added to the USGS foreign volumes to obtain world totals.

FIGURE 2 12 EIA World Conventional Oil Production Scenarios.

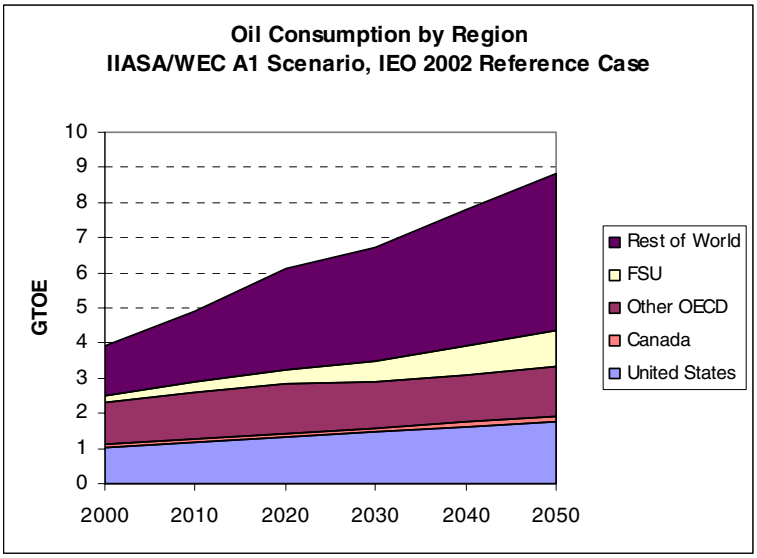


FIGURE 3 Oil consumption by region.

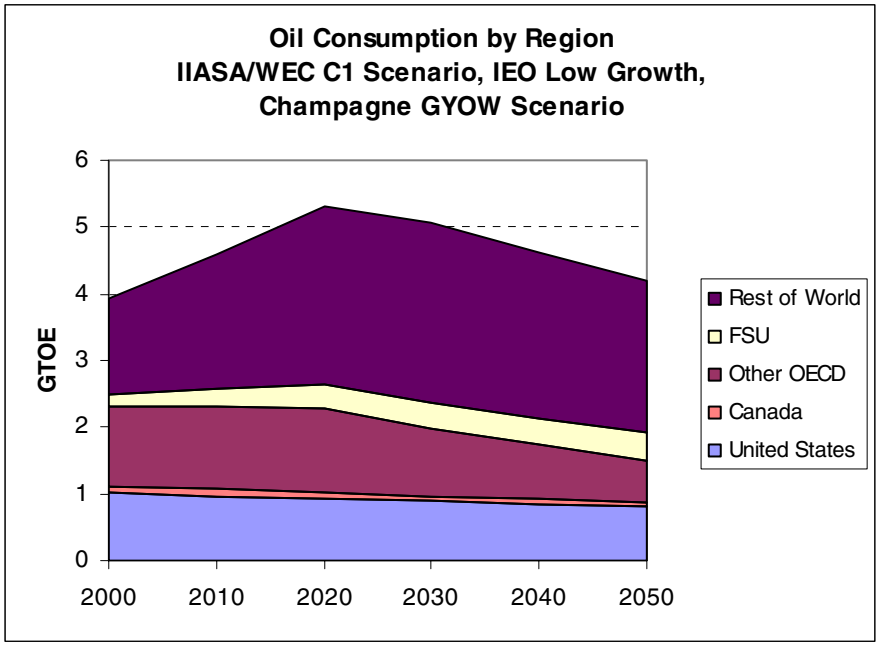


FIGURE 4 Oil consumption by region, IIASA/WEC C1 Scenario, IEO low growth, Champagne GYOW Scenario.

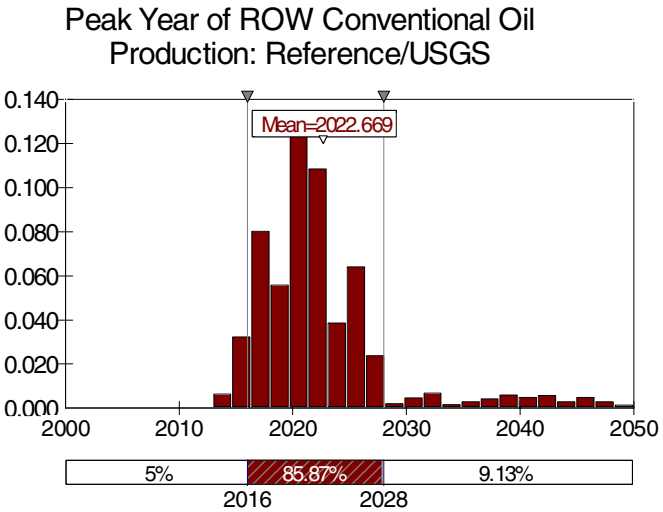


FIGURE 5 Peak year of ROW conventional oil production: reference/USGS.

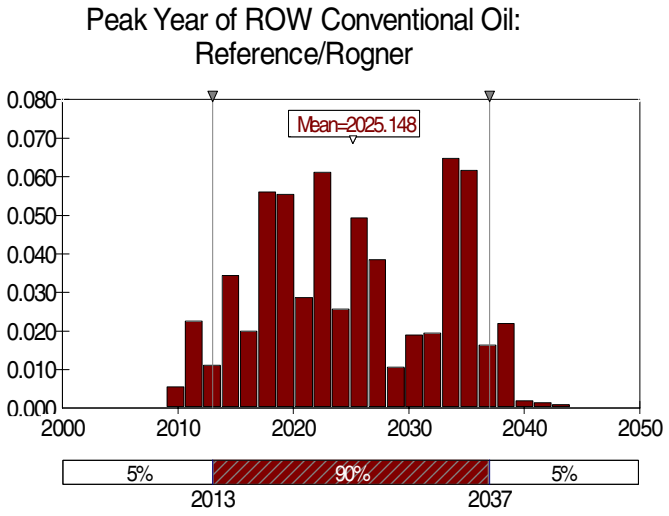


FIGURE 6 Peak year of ROW conventional oil: reference/Rogner.

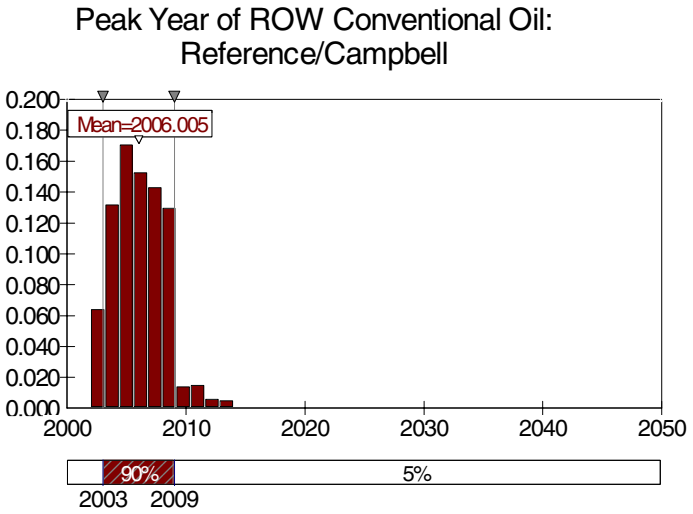


FIGURE 7 Peak year of ROW conventional oil: reference/Campbell.

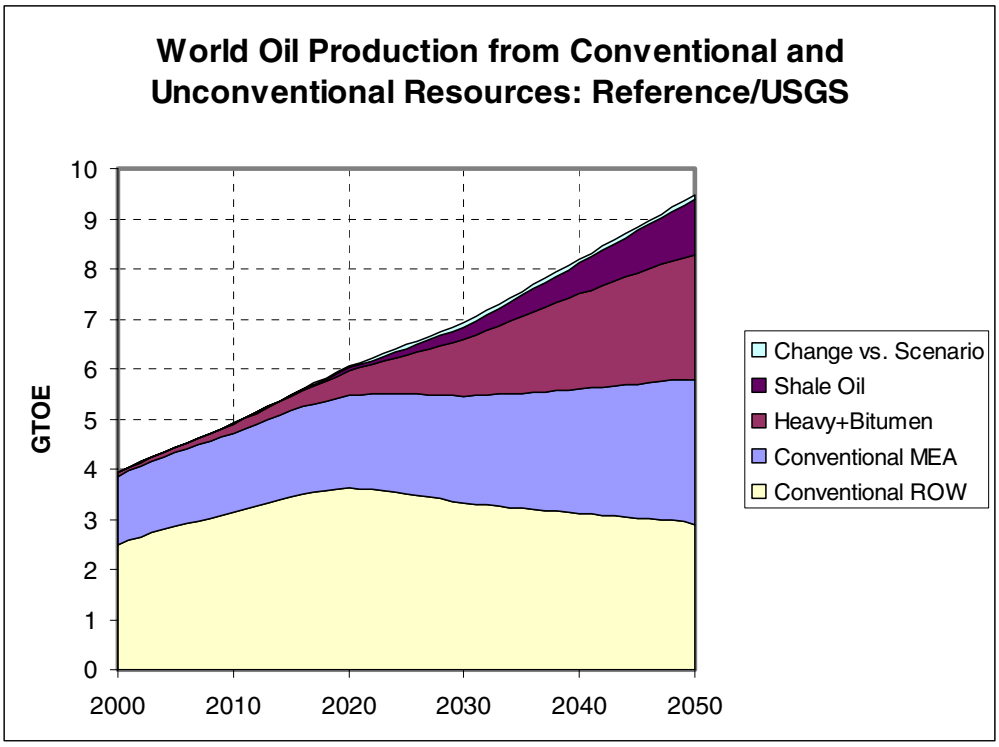


FIGURE 8 World oil production from conventional and unconventional resources: reference USGS.

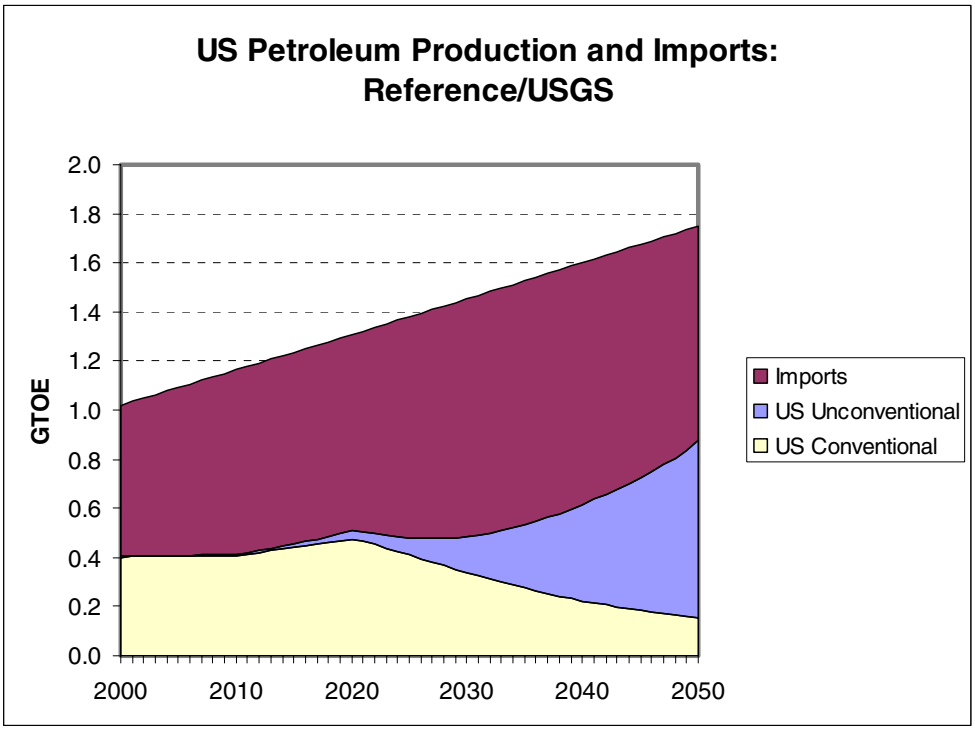


FIGURE 9 U.S. petroleum production and imports: reference/USGS.

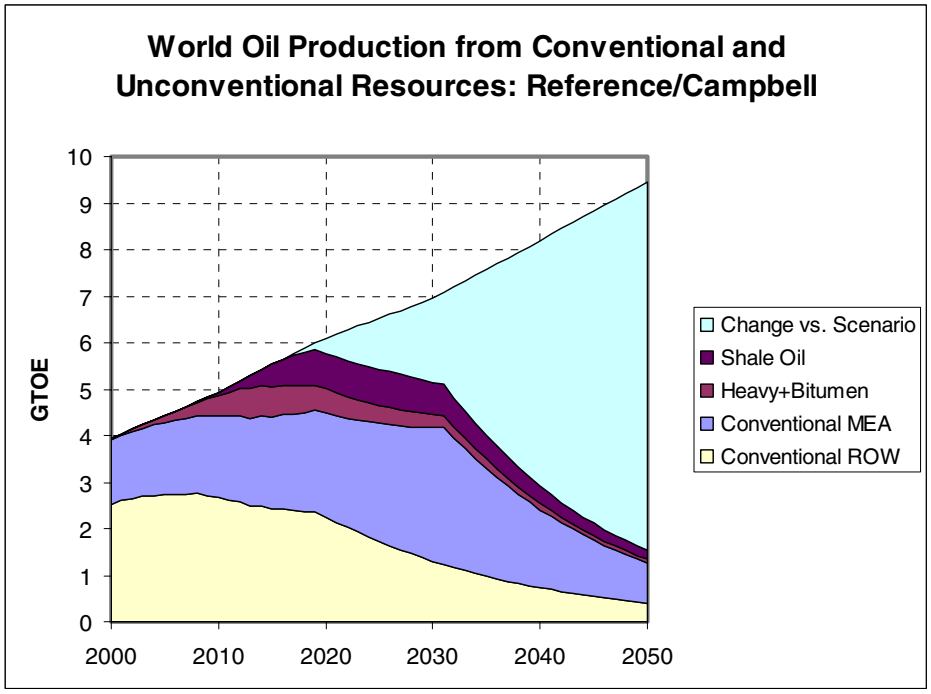


FIGURE 10 World oil production from conventional and unconventional resources: reference/Campbell.

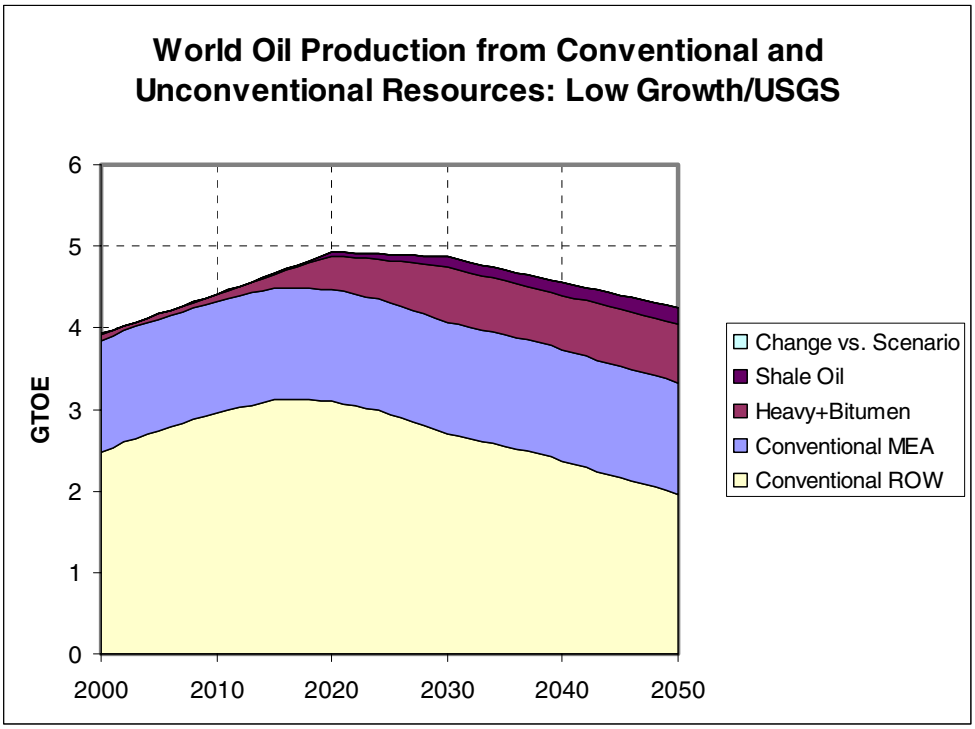


FIGURE 11 World oil production from conventional and unconventional resources: low growth/USGS.

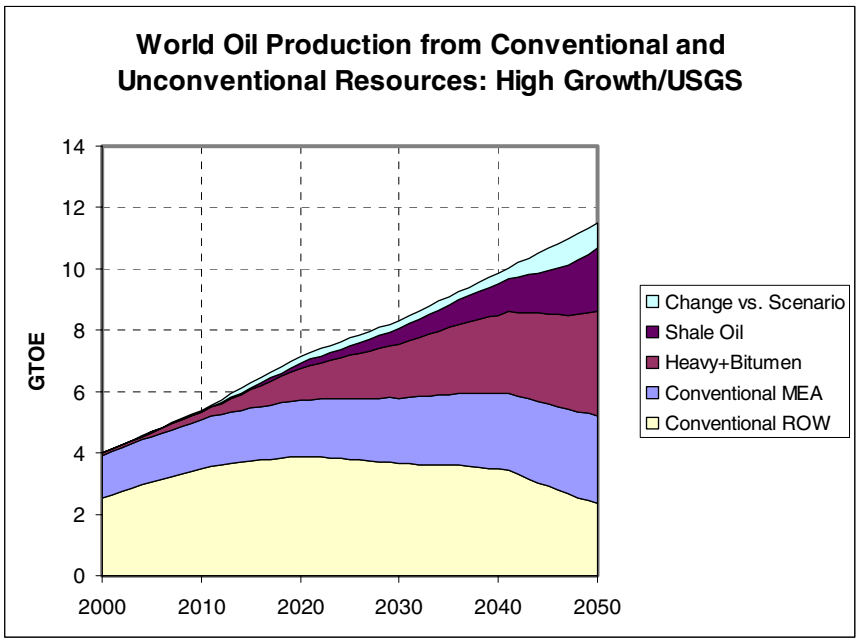


FIGURE 12 World oil production from conventional and unconventional resources: high growth/USGS.

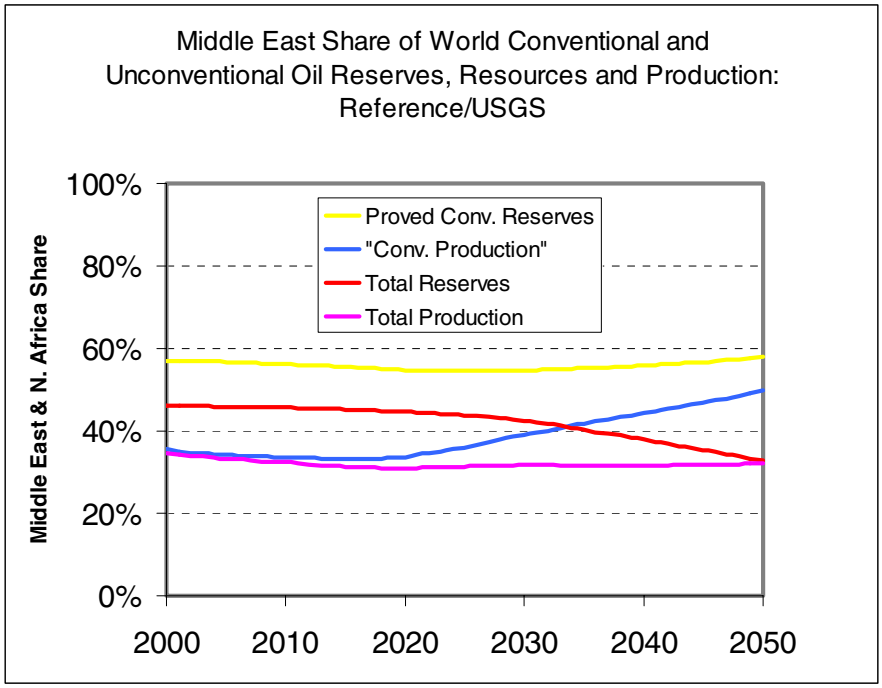


FIGURE 13 Middle East share of world conventional and unconventional oil reserves, resources and production: reference/USGS.

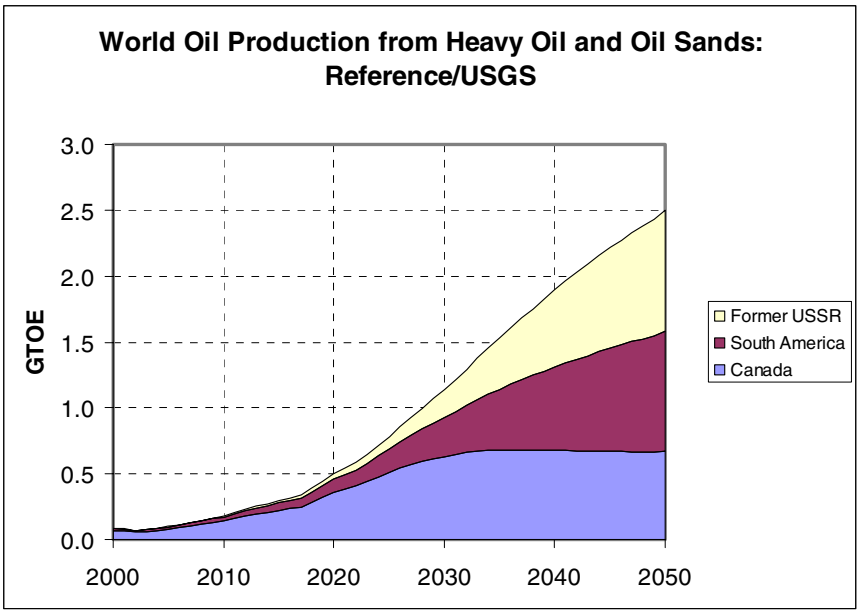


FIGURE 14 World oil production from heavy oil and oil sands: reference/USGS.

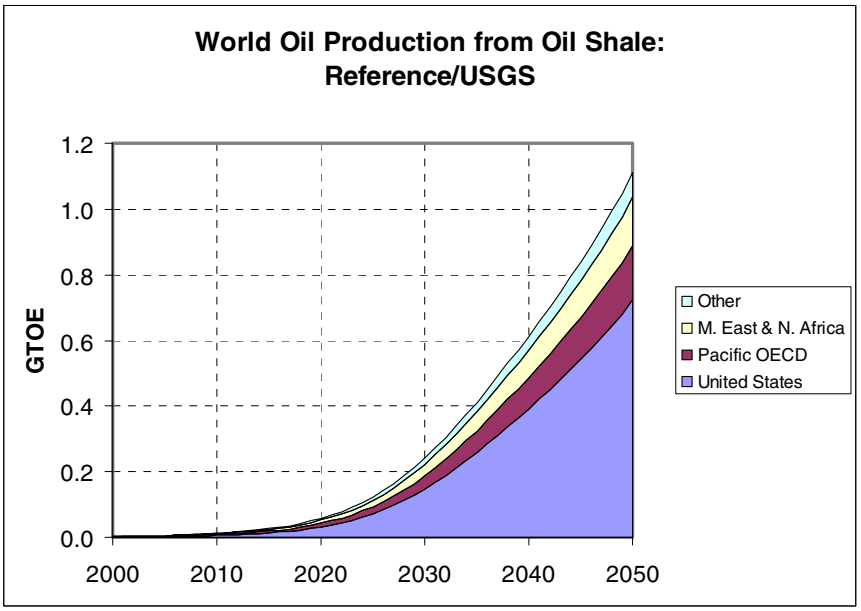


FIGURE 15 World oil production from oil shale: reference/USGS.