Running Out of and Into Oil

Analyzing Global Oil Depletion and Transition Through 2050

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A risk analysis is presented 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 U.S. Geological Survey (USGS) and C. J. Campbell provide alternative views of ultimate world oil resources. A global energy scenario created by the International Institute of Applied Systems Analysis and the World Energy Council provides the context for the risk analysis. A model of oil resource depletion and expansion for 12 world regions is combined with a market equilibrium model of conventional and unconventional oil supply and demand. The model does not use 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 resource assessment 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 after that date. 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, oil sands and heavy oil from Canada, Venezuela, and Russia and, later, shale oil from the United States must expand rapidly if total world consumption of petroleum fuels is to continue to increase.

Hubbert's strikingly accurate prediction of the peak of U.S. oil output is a powerful reminder that conventional oil resources are indeed finite (*1*). Additionally, 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., see Odell (*3*)]. Yet, to assume that whatever advances are needed will occur, and at the rates needed to ensure 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 appears 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 increase. 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*) (Figures 1–7). The most recent estimates by the U.S. Geological Survey (USGS) appear to be an exception to that rule, but the apparent disagreement is largely attributable to a change in definitions (*8*). 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 account for nearly all the difference between the USGS's 1994 and 2000 mean estimates (*9*).

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. 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 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 gas and coal could also be used and that it is the goal of U.S. energy policy to make a transition to hydrogen produced substantially from renewable energy sources. Those options are not considered.

Several recent studies have considered the timing of the peaking of conventional oil production (*10–16*). 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. All of Wood's scenarios suggest catastrophically rapid transitions once conventional oil production peaks. Cavallo 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 from 2015 to 2020 (*13*). Manne assumed the USGS 2000 5% probability case as a reference that produced an estimate of 2040 for the peak in world oil production (*17*). A low resource case assuming only 50% of the undiscovered resources of his reference case produced a peak in 2020. This study uses an integrated model of the depletion of conventional oil and the transition to unconventional oil resources to carry out a risk analysis. Probability distributions are assumed for key parameters affecting (*a*) the quantity of conventional oil resources available, (*b*) rates of technological progress, (*c*) oil production by Middle Eastern producers, and (*d*) other economic assumptions. 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 this sense, the authors believe it is fair to characterize this study as having an optimistic bias. The model is described in detail by Greene et al. (*18*).

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Transportation Research Record: Journal of the Transportation Research Board, No. 1880, TRB, National Research Council, Washington, D.C., 2004, pp. 1–9.

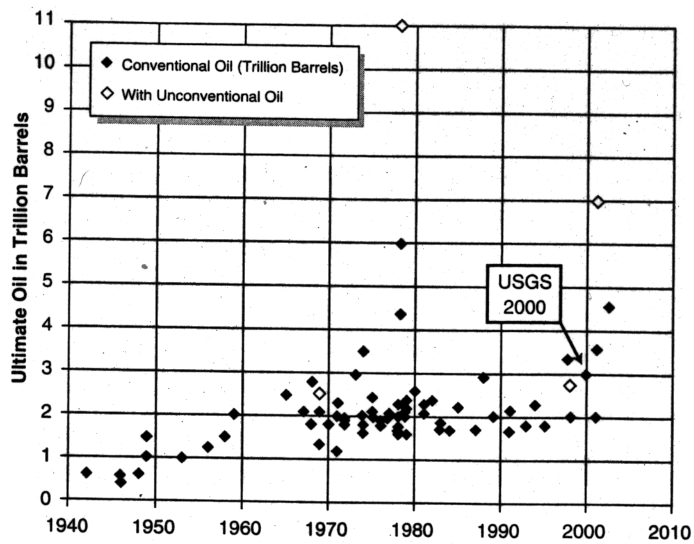

FIGURE World's oil (and liquids) ultimates (7).

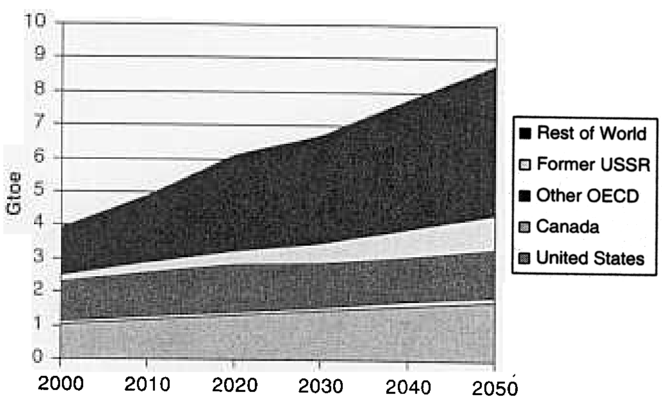

FIGURE 2 Oil consumption by region—IIASA/WEC A1 Scenario, IEO 2002 Reference Case.

The threat of global climate change gives reason to be concerned about a transition from conventional to unconventional oil resources. As Grubb 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 (*5*).

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 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.

WHAT IS OIL?

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. Oil available through enhanced recovery is also considered conventional oil in this report. Conventional oil resources are also defined here to include natural gas liquids (NGLs) because a large fraction of these liquids are ultimately consumed as petroleum products (even though the production of NGL depends on the production of natural gas, not oil) (*6*). Unconventional oil comprises

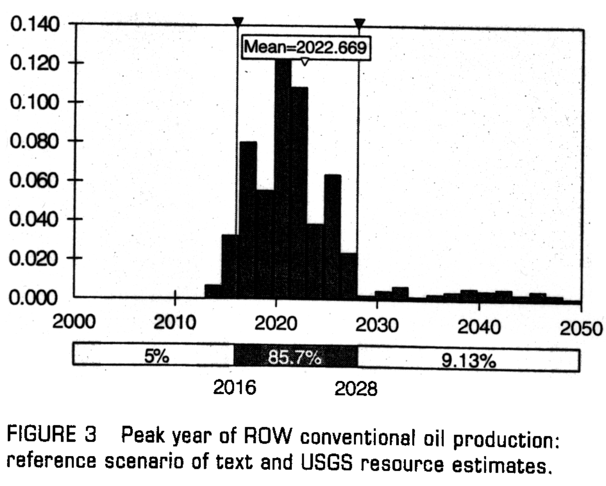

FIGURE 3 Peak year of ROW conventional oil production: reference scenario of text and USGS resource estimates.

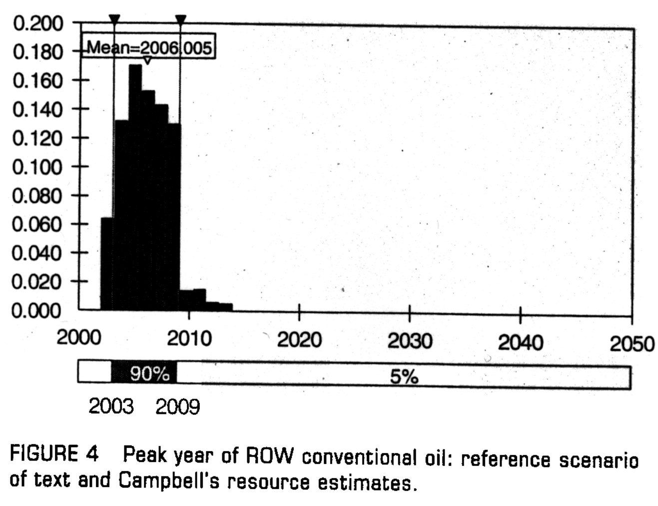

FIGURE 4 Peak year of ROW conventional oil: reference scenario of text and Campbell's resource estimates.

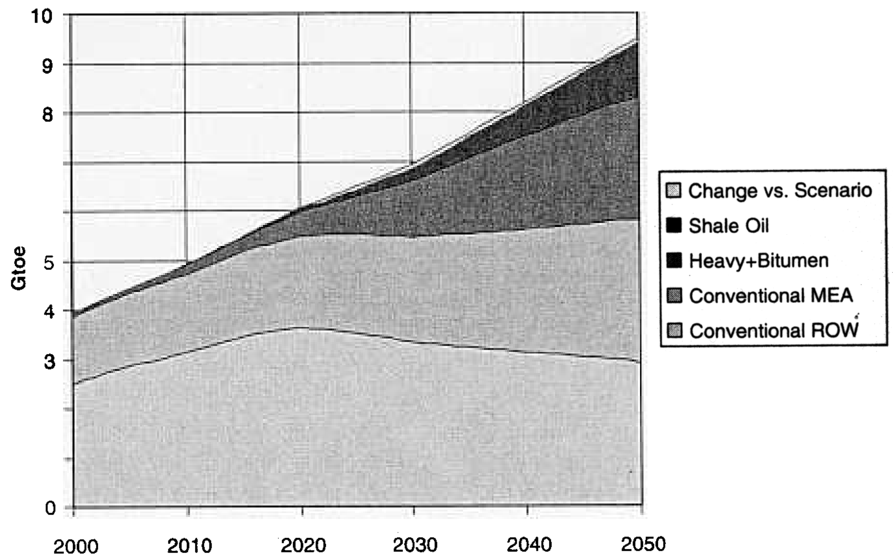

FIGURE 5 World oil production from conventional and unconventional resources: reference scenario of text and USGS resource estimates.

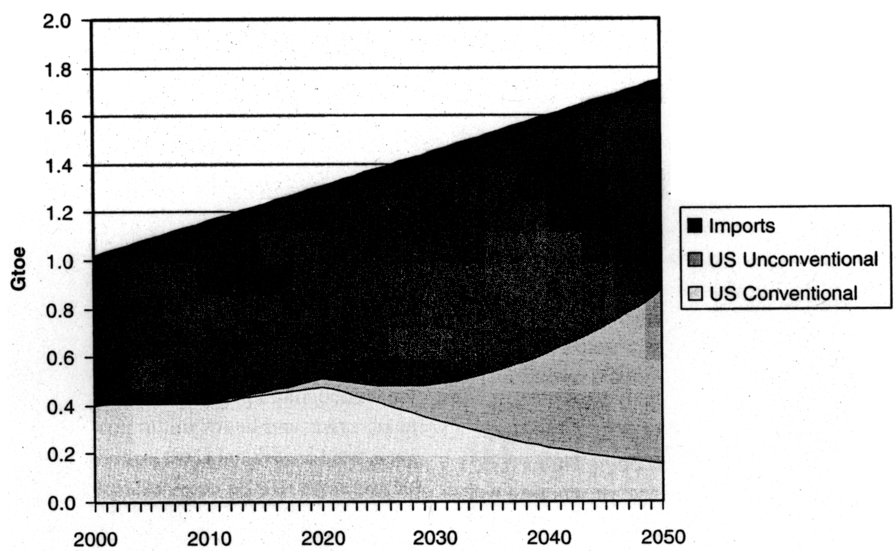

FIGURE 6 U.S. petroleum production and imports: reference scenario of text and USGS resource estimates.

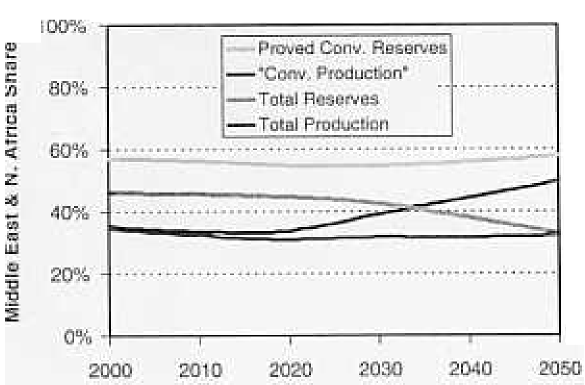

FIGURE 7 Middle East and North Africa (MEA) share of world conventional and unconventional oil reserves, resources, and production: reference scenario of text and USGS resource estimates.

deposits of greater density than water (e.g., heavy oil), viscosities in excess of 10,000 centipoise (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, whereas others argue that because of the cost and complexity of operations, water scarcity, and other factors Canadian oil sands should remain unconventional (*19*). As Adelman notes, 50 years ago offshore crude oil was considered an unconventional resource. From that 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 (*20*).

RESOURCE ESTIMATES USED IN THIS STUDY

In the analyses described here, two sets of resource estimates are used.

TABLE 1 Estimates of World Petroleum Resources from 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 NGL resources remaining under any category. These are included with oil.

- USGS 2000 conventional oil estimates plus unconventional oil estimates synthesized from USGS, World Energy Council (WEC), and International Energy Agency (IEA) as described below (*8*) and
- Estimates based on C. J. Campbell's year-end 2002 global assessment (*21*).

The USGS estimates also reflect the following premises: (*a*) that technological progress will significantly expand ultimate resources and (*b*) that there is considerable uncertainty about how much oil remains to be found. Campbell is far less sanguine about the ability of technology to expand resources and is more confident about how much oil remains (*21*).

The USGS 2000 estimates are available by country, which allowed them to be rearranged into 11 world regions [the same regions used by Nakićenović et al. (*22*)]. Campbell's global total 2002 estimates were distributed to countries on the basis of each country's share of his own year-end 1999 estimate, which is available by country (*23*). The procedures and data are described by Greene et al. (*18*).

In addition to median estimates, the USGS 2000 study provides mean (expected value) estimates and 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 it is 3.3 trillion. All these estimates include cumulative production to 2000 of 0.54 trillion barrels (Table 1).

In addition to proved reserves, two other categories of conventional oil are defined:

- Estimated additional resources, equal to the USGS's 50th percentile estimate of undiscovered oil or Campbell's "future" production (Table 2), and
- Speculative resources, equal to the difference between the USGS's 50th percentile and 5th percentile estimates and zero when Campbell's data are used.

TABLE 2 Estimates of World Oil Conventional and Unconventional Oil Resources by Campbell, at Year-End 2002

Resource Category	Estimated Quantity (billion barrels)	
Conventional Oil		
Known Fields Produced	896	Cumulative production
Known Fields Future Production	871	"Proved reserves"
New Fields Future Production	133	Estimated additional resources
Deepwater Future	60	Estimated additional resources
Polar Future	30	Estimated additional resources
Gas Liquids	400	"Proved reserves"
Total Conventional	2390	
Heavy Oil (unconventional)	300	Unconventional

HEAVY OIL AND BITUMEN (TAR OR OIL SANDS)

Estimates of unconventional oil resources produced by Rogner (*24*) can be compared with estimates derived from other sources: USGS (*25*), WEC (*26*), and IEA (*27*). Recoverable reserves of bitumen (oil and tar sands) and heavy oil appear to be highly concentrated in three regions: (*a*) Alberta, Canada; (*b*) the Orinoco Oil Belt of Venezuela; and (*c*) the former USSR (Russia) (Table 3). The derivation of the estimates shown in Table 4 can be found in Greene et al. (*18*). In regard to total unconventional oil resources, the estimates derived from IEA/WEC/USGS estimates compare well with Rogner's estimate of 381 gigatons oil equivalent (Gtoe) of Category V and VI resources. A comparison at the regional level, however, reveals considerable disagreement reflecting the higher level of uncertainty about those resources. The division of unconventional oil resources into oil shale versus heavy oil and oil sands leads to a dichotomy of regions. If the North American region is divided into Canada and the United States, it appears that every region can be described either as oil sands and heavy oil dominant or as oil shale dominant. Only the former USSR and Latin America appear to have significant quan-

TABLE 3 Estimates of World Oil Sands and Oil Shale Resources from Three Sources

	Based on IEA/WEC/USGS				
Region	Oil Shale (Gtoe)	Heavy Oil & Oil Sands (Gtoe)	Share Heavy Oil & Oil Sands (%)	Total Unconv. (Gtoe)	Rogner 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
Former USSR	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 United States 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 United States.

TABLE 4 Distribution of 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 (bbl)]			
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.

tities 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 preexisting 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. Details of this model including the equations used are presented by Greene et al. (*18*).

Proved reserves are treated as the stock from which current production is drawn and to which additions are made from other resource categories (*28*). If possible, the full amount of a region's production 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 Reserves/(Reserves/Production) [R/(R/P)*] can be supplied. The rest is set aside as potential demand for unconventional oil.

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., Bentley et al. (*6*)]. On the other hand, economists might argue that the Hubbert theory is overmechanistic and that if peaking ever occurs it will be determined more by economics and technology than by geology [e.g., Odell (*3*)]. By adopting the R/P rule, the authors 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. All three types of conventional resources (proved, estimated additional, and speculative) are augmented by reserve growth at a user-specified annual rate as long as resources remain in the "reserve growth" category. That 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. 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 is not unlimited. Once the amount estimated by the USGS has been used up, reserve growth stops.

The WESM model was designed to use the world energy scenarios created by the International Institute of Applied Systems Analysis (IIASA) and WEC through 2050 (*22*). IIASA/WEC scenarios were then adjusted to match the U.S. Department of Energy International Energy Outlook (IEO) 2002 Reference Case projection to the year

2020 (*29*). Beyond 2020 variables were trended back toward 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 was also calibrated to detailed transportation energy forecasts developed by the U.S. Department of Energy and Natural Resources Canada using the Champagne model (*30, 31*).

Transition to Unconventional Oil

Proved reserves of unconventional oil are the stock from which all unconventional oil is produced. Additions to proved reserves of unconventional oil are drawn from remaining unconventional resources with the use of a function that attempts to maintain the target R/P ratio for unconventional reserves. No reserve growth is assumed. Details are provided by 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 that 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 on the basis of 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. That becomes a serious constraint in model runs using resource estimates based on Campbell (*21*).

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

SCENARIOS OF WORLD ENERGY SUPPLY AND DEMAND

World energy use and supply scenarios were taken from the IIASA/WEC study, *Global Energy Perspectives* (*22*), and from forecasts of international energy use to 2020 by the U.S. Energy Information Administration (*29*). Results presented here are based on IIASA/WEC 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" (*22*, p. 8). Other scenarios are explored by Greene et al. (*18*).

In this scenario world population grows from 5.3 billion in 1990 to 10.1 billion by 2050. Gross world product (GWP) increases from \$20 trillion (1990 US\$) in 1990 to \$100 trillion, and total world primary energy use increases from 9 Gtoe to 25 Gtoe. The energy intensity of GWP is assumed to decrease at the rate of –0.9% per year.

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 (AEO) 2002 Reference Case forecast to 2020. In the IEO 2002 Reference Case, world energy use increases from 9.6 Gtoe (350 quadrillion BTUs, at 40.4 quadrillion BTUs/Gtoe) in 1999 to 15.4 Gtoe by 2020 (*29*). After 2020, a splining method [see Greene et al. for details (*18*)] was used to trend the AEO-adjusted projection back toward the appropriate IIASA/WEC scenario. North American oil use projections based on the Champagne model (*30, 31*) were substituted for the IIASA/WEC scenarios' North American oil use projections [details are provided by Greene et al. (*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 4 Gtoe in 2000 to 9 Gtoe in 2050 (Figure 2). Increases in the Organisation for Economic Co-operation and Development outside the United States and Canada are modest (1.1% per year), whereas in the developing world oil use increases at 2.6% per year for an overall world growth rate of 1.9% per year.

RISK ANALYSIS OF OIL PEAKING AND TRANSITION

Risk analyses were conducted for the two resource scenarios using the @Risk® software package (*32*). 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 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 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. Distributions are calculated for the years in which world conventional oil production peaks, and the year in which oil production outside the Middle East peaks, as well as the volumes of oil produced at peak production.

The probability distributions used for 14 key parameters are shown in Table 4. In every case the parameters are assumed to follow the uniform distribution because it is the simplest. However, uniform distribution function gives greater weight to extreme values than most other distribution functions. Greene et al. provide a discussion of the choices of parameter values (*18*).

RESULTS

Peaking of Conventional Oil

The resulting distributions of the peak year of conventional oil production from "rest-of-world" (ROW) countries (outside the Middle East) are shown in Figures 3 and 4. 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 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 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. More important, as will be seen below, world conventional production after 2025 is likely to be quite flat, so that even if the peak is delayed, a large and growing gap will open up between demand and conventional oil production, a gap that must be filled by unconventional oil. But the simulations using resource estimates based on Campbell point to 2015 as the expected date of peak world conventional oil production.

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 transition paths, one can obtain a better picture of the way oil production and resource depletion are evolving over time.

Reference Scenario at Median Parameter Values

Total world oil consumption, conventional plus unconventional, increases from 4.0 Gtoe in 2000 to 9.5 Gtoe in 2050 when the reference scenario, mean parameter values, and USGS-based resource estimates are used. Conventional oil production outside the Middle East (ROW) peaks in 2020 at 3.6 Gtoe (Figure 5). The decline in ROW oil production after the peak is relatively slow, about –0.75% per year during the next 20 years. Duncan reports that of 24 nations whose oil production has already peaked, the average rate of decline in output has been only –0.23% per year (*14*). 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% per year in the reference scenario. If Middle East output is assumed to remain constant, the postpeak rate of decline in ROW output is only –0.45% per year.

U.S. oil imports increase very slowly through 2020 (Figure 6). The WESM model estimates that U.S. conventional production can remain flat and even increase slightly until about 2020, as a result of increasing oil prices (to about $30/barrel) 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. conventional oil production must be considered optimistic, given that U.S. production peaked in 1970. That 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.

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 2006, 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. After that, the situation falls 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.

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.

With the use of the reference scenario and the USGS-based resource estimates, one can see that 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 7). 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. For example, if the Middle East maintains a steady rate of increase in output of 3% per year, 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; 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.

Sources of Unconventional Oil

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: (*a*) the type of unconventional oil a region possesses and (*b*) the quantity it is estimated to hold.

Considering the reference scenario and the USGS-based resource estimates, oil sands from Canada are the initial major source of unconventional oil supply (Figure 8). Canadian oil sands production increases rapidly to about 0.7 Gtoe [14 million barrels per day (mmbd)] by about 2034 and then remains nearly flat through 2050. The specific pattern of Canadian supply should not be taken too seriously because it depends partly 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 regard to water availability, upgrading requirements, energy consumption, environmental impacts, and infrastructure needs (*33*). 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, 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, the majority of it from the United States (Figure 9). 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 depend on a number of critical assumptions, nearly all of which are debatable. It is believed that the 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, 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 the USGS 2000 survey are used,

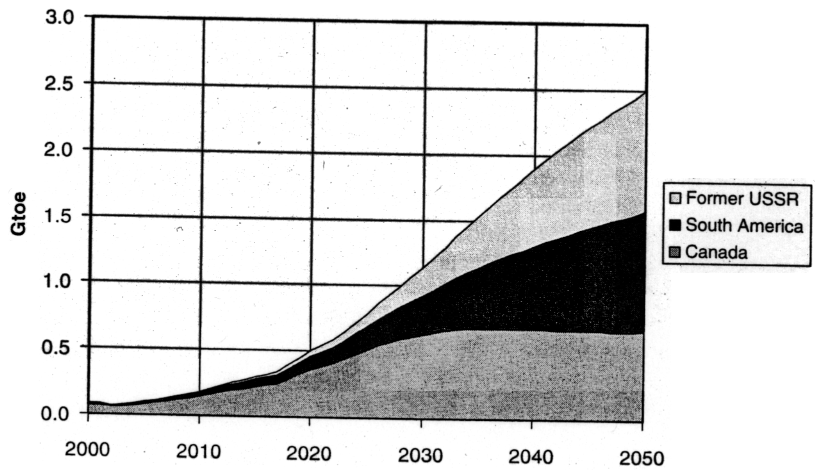

FIGURE 8 World oil production from heavy oil and oil sands: reference scenario of text and USGS resource estimates.

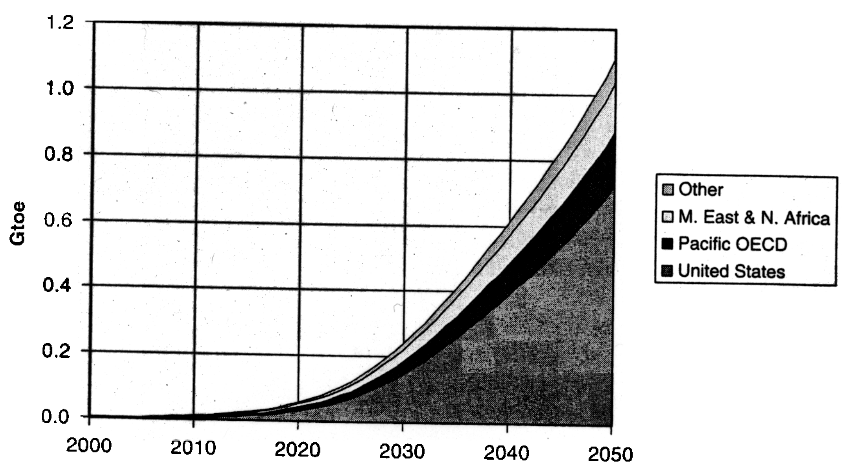

FIGURE 9 World oil production from oil shale: reference scenario of text and USGS resource estimates.

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 under way.

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. 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% to 9% per year 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. That is not likely to happen until after 2025, if then. If the WESM model's predictions of flat or increasing U.S. oil output for the next decade or more are overoptimistic (as they probably are), the near-term increase in U.S. imports will be greater still.

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