RUNNING INTO AND OUT OF OIL: SCENARIOS OF GLOBAL OIL USE AND RESOURCE DEPLETION TO 2050

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1. INTRODUCTION

Past warnings that the world will soon "run out of oil" have been compared with the fable of the shepherd boy who cried, "Wolf!" (Martin, 1999). Each time the warnings have proven to be unfounded. In the fable, the wolf finally did appear, but the townspeople, assuming yet another false alarm, failed to respond when the danger was real. The sheep were devoured. The world's oil resources are unquestionably finite, and world oil consumption continues to grow. Could it be that this time the warnings are correct, and will they be unheeded because we refuse to be fooled one more time (e.g., Bentley, 2002, Campbell and Laherrere, 1998)?

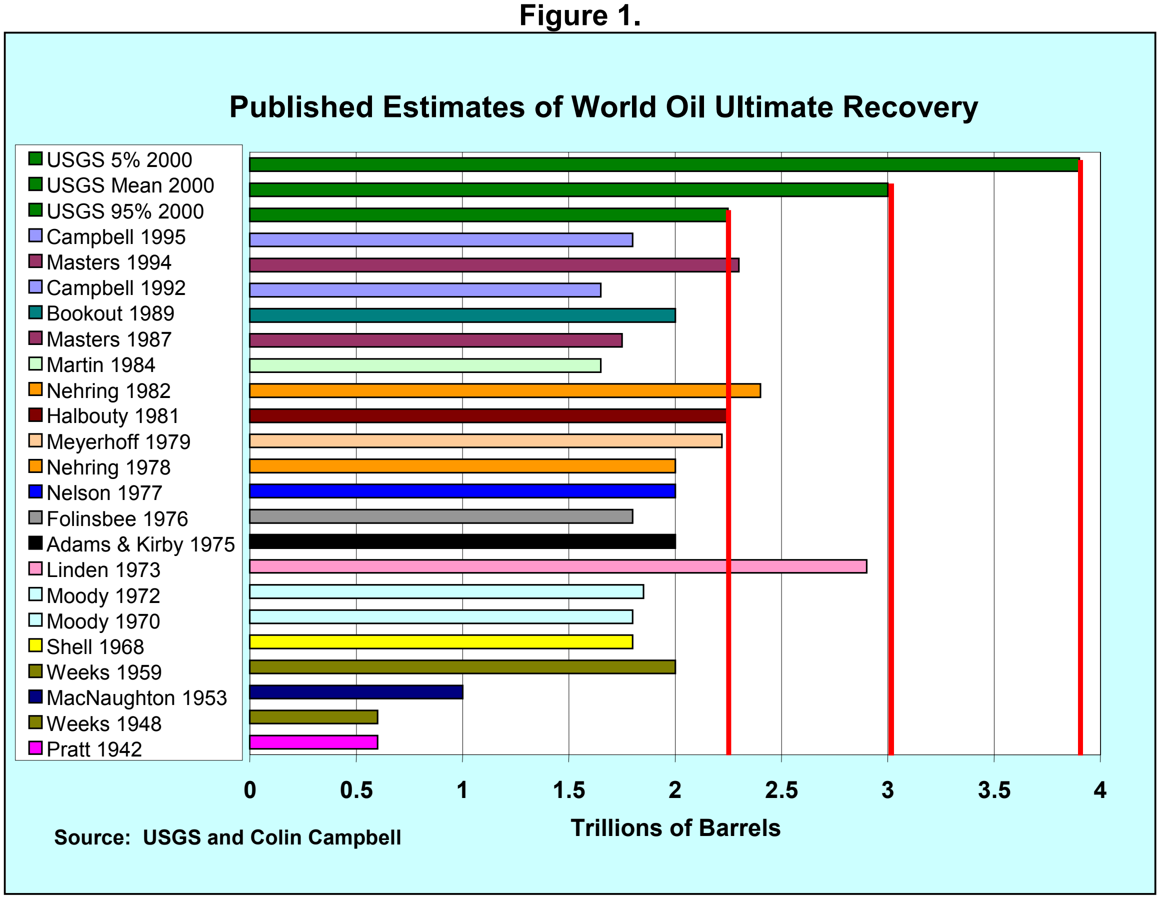
Historical predictions of the end of oil have been wrong because they underestimated both the size of the world's oil resources and the degree to which technology could expand the resource base. Oil resources are not a fixed quantity, but a variable that depends on the states of earth science and technology (Adelman and Lynch, 1997). The possibility that technological change could greatly expand the base of exploitable hydrocarbon occurrences must be acknowledged (e.g., Odell, 1999). However, to **assume** that whatever advances are needed **will** occur, and in amounts adequate to assure plentiful supplies of low-cost oil, amounts to faith. Adelman and Lynch (1997) expressed their belief in this way: "*Some powerful force* is at work to offset depletion…." (emphasis added).

On the other hand, as knowledge of the earth's crust increases, the comprehensiveness and precision with which hydrocarbon occurrences can be characterized increases. Apparent evidence of this is the fact that estimates of total available resources of conventional oil have changed little since 1960 (Grubb, 2001; Bentley et al., 2000; also Figure 1). In addition, the most recent estimates by the U.S. Geological Survey (USGS, 2000) explicitly include the potential for reserve growth due to advances in technology and knowledge of deposits. That is, they carefully estimated the potential for technological change and increased knowledge to expand usable oil resources.

Is current information now reliable enough to be the basis for action? Several recent studies have considered the timing of the peaking of conventional oil production (e.g., Wood et al., 2000; Bentley 2002; Laherrere and Campbell, 1998; Cavallo, 2002). This will be an extremely significant event, since it will mark the point at which the world **must** begin a transition to an alternative source of energy. A very likely candidate, though certainly not the only one, unconventional fossil oil resources. This study attempts to integrate modeling of the peaking of conventional oil with transition to unconventional oil in a systematic framework that permits analysis of sensitivity to a variety of key factors. Physical exhaustion of as critical a natural resource as oil, in the absence of suitable substitutes, could have serious consequences for the global economy. The failures of past predictions of oil depletion are not prudent grounds for dismissing the best current estimates. It is critically important that this issue be analyzed using the best available data, and using methods that acknowledge and quantify uncertainties.

These are difficult questions to which there is no simple answer. First, as far as geological science has progressed, there is still incomplete knowledge of what lies beneath the surface of the earth. Some oil deposits remain to be discovered, and the true extent of known deposits is often unclear. Second, technological change will redefine the boundaries of producible resources and the costs of production. Advances in deep-water drilling have opened up new offshore resources and techniques such as horizontal drilling have increased recovery rates from known reserves (Alazard, 1996). Third, technological, economic and societal changes will alter the relative value of energy sources, possibly leading the world's economies away from oil well before exhaustion of oil resources is a problem. Indeed, as it has been said, the oil age may not end for lack of oil any more than the Stone Age ended for lack of stones.

Figure 1.



Source: USGS and Colin Campbell

Although some argue that it is a certainty that markets, motivated by higher prices, will find viable substitutes for oil (e.g., Davies and Weston, 2000), in fact, this is no more or less than a plausible assertion. It is true that potential unconventional oil resources are vast, and are already beginning to be developed, particularly in Venezuela and Canada. Further technological advances could extend the range of usable resources to include even shale oil (Odell, 1999). Although one may try to predict how these three factors will determine future oil availability, substantial uncertainty about both timing and magnitude will remain. There is not guarantee of inexhaustible, cheap oil.

The threat of global climate change is another important reason to be concerned about a transition from conventional to unconventional oil resources. Such a transition is highly likely, because of the compatibility of unconventional oil with existing infrastructure. Unfortunately, as Grubb (2001) and others have pointed out, the longer-term problem of climate change depends on the world's decision to use or not to use unconventional oil and gas, and coal.[1] There is not enough carbon in all the world's conventional oil and gas resources to raise atmospheric carbon

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[1] Or to capture and sequester the carbon of these fossil resources so that it is not released to the atmosphere.

concentrations above the threshold of 450 ppm[2] (Grubb, 2001, p. 838). To reach the higher levels that may cause drastic climate changes will require tapping into unconventional oil and gas resources, and coal. This fact alone gives meaning to the distinction between conventional and unconventional fossil energy resources.

Of course, the world could go partway down the path of developing unconventional oil resources, and later reverse direction. But such a strategy would strand huge investments in the more capital-intensive production and refining of unconventional oil. If the transition to unconventional oil is gradual, a reversal might not be too costly. But if it is massive and rapid, the world's economies could quickly become locked into a high carbon future. Avoiding the path of unconventional fossil resources would greatly increase the world's chances of successfully dealing with global climate change.

A global transition to unconventional oil could also shift the balance of power in world oil markets. The U.S. National Energy Policy declared that the nation's dependence on petroleum in a cartel-dominated world oil market posed continued and growing economic and national security problems (NEPDG, 2001, pp. 1-11 to 1-13). Could a transition to unconventional oil help alleviate those problems by undermining OPEC's market power, or can OPEC maintain or even increase its market dominance despite such a transition?

Is a transition from conventional oil imminent? Is it likely to lock the world into a high-carbon energy future? Will it undermine or strengthen OPEC's influence over world oil markets? This report attempts to shed some light on these questions by simulating the transition to unconventional oil, and testing the sensitivity of its timing and speed to: (1) the quantity and rate of expansion of conventional oil resources, (2) alternative scenarios of world energy production, (3) technological change affecting the costs of conventional and unconventional oil production, (4) OPEC production decisions. The results cannot be considered definitively conclusive. Yet, they clearly suggest that the issue of conventional oil depletion cannot be lightly dismissed, and that it is not all too soon to begin serious examination of transitions away from conventional oil. The model used in this assessment is described in detail in the appendix.

2. WORLD OIL RESOURCE ESTIMATES

2.1 WHAT IS OIL?

In any assessment of world oil resources, the first question to be answered is, what is oil? (Laherrere, 2001). 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. If such hydrocarbons require enhanced recovery techniques, Laherrere (2001) and Rogner (1997) consider them to be unconventional oil. In this report, oil available via enhanced recovery is considered conventional oil but its exploitation is treated differently from other conventional oil. Conventional oil resources are also defined here to include all petroleum, that is, to include natural gas liquids, since most of these liquids end up being consumed as petroleum products. Unconventional oil comprises

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[2] Of course, this will partly depend on which estimates of conventional oil resources are correct.

deposits of greater density than water (e.g., heavy oil), viscosities in excess of 10,000 cP (e.g., oil sands), or occurs in tight formations (e.g., shale oil). As Rogner (1997) has pointed out, the definition of unconventional oil is somewhat flexible and depends in part on the state of oil recovery technology.

Bentley et al. (2000) correctly notes that NGL production is dependent on the production of natural gas and not oil and so he excluded it from his "peaking" estimations. Combining NGL resources, as is done here, implicitly assumes that natural gas production will conveniently provide NGLs to the petroleum market, as they are needed.

2.2 ARE OIL RESOURCES INCREASING OR DECREASING?

The perception that estimates of world oil resources have uniformly increased over time is not consistent with estimates made since about 1960 (e.g., Grubb, 2001; Bentley, 2002; Bentley et al., 2000). As Figure 1 (Wood et al., 2000) shows, estimates of ultimately recoverable world crude oil resources have been in the vicinity of 2 trillion barrels for the past 40 years. This trend suggests a growing consensus, probably resulting from the accumulation of knowledge about the earth's geology.

The recent assessment of the USGS (2000) appears to be an exception, since its median estimate is 2.9 trillion barrels, about 40 percent higher. However, a large part of the apparent difference is one of definition. The USGS study includes, for the first time, an estimate of reserve growth that amounts to 0.7 trillion barrels. None of the other studies estimate reserve growth. Excluding this newly defined category, the USGS 2000 estimate is 2.2 trillion barrels, relatively consistent with other estimates developed over the past 40 years. Including reserve growth is an important new feature of the USGS 2000 study, since it explicitly estimates the future effects of potential technological advances. On the other hand, it is not uncontroversial.

The USGS also estimated world resources of natural gas liquids (NGL), many of which find their way into petroleum products. NGLs are not counted among crude oil resources and they are not included in the oil resource estimates discussed in the previous paragraph or shown in Figure 1. However, NGLs are generally counted in petroleum consumption. Throughout this report, NGLs are included as conventional oil resources.

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 natural gas liquids. The upper including NGLs are 4.4 trillion barrels. The mean estimate for crude oil is 3.0 trillion, for petroleum 3.3 trillion. All these estimates include cumulative production to date of 0.54 trillion barrels (Table 1).

Estimates of both conventional and unconventional world hydrocarbon resources developed by Rogner (1997) are used as a framework for organizing oil resource data by region and type. Rogner's estimates are subdivided into 11 world regions, the same regions used in the International Institute for Applied Systems Analysis/World Energy Council (IIASA/WEC) study of global energy scenarios to 2100 (Nakicenovic et al., 1998). Eight categories of resources are distinguished. Category I corresponds to proved recoverable reserves. Category II includes occurrences that have not been discovered, but have a "reasonable probability of being discovered." They are comparable to the USGS 50th percentile or mean undiscovered resources. Category III represents more speculative occurrences, and should be compared with the difference between the USGS 5th and 50th percentile estimates. Interpreted in this way, the most probable amount of Category III resources (according to the USGS) is zero. This category is useful for quantifying one's optimism about future discoveries. Category IV estimates the potential for enhanced recovery. Historically, only about 34 percent of in situ oil has been recovered. Rogner assumes that in the future this will increase to 40 percent, and this assumption has already been incorporated in his estimates of Category I-III resources. Category IV represents further improvements in recovery rates. Rogner includes category IV with unconventional oil resources. They are counted in the analysis below as conventional oil.

Table 1. 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 US 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 US 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.

Unconventional resources are represented in categories V-VIII. Category V comprises identified reserves of unconventional oil that can be produced today, or in the near future at current market prices. This includes, for example, certain 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 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 the assessment of unconventional resources through 2050 (Table 2). This assumption is intended to exclude low-grade shale oil and all oil unrecoverable after enhanced recovery.

Others argue that the USGS and Rogner assessments overestimate ultimately recoverable conventional oil resources, and that unconventional resources are likely to be inadequate to fill the gap between demand and supply once conventional oil production peaks (Bentley, 2002; Laherrere, 2001; Bentley, et al., 2000). They attribute the overestimation to several key factors, including the following:

Table 2. Estimated World Oil Resource Occurrences, in Gigatonnes of Oil Equivalent (Gtoe) (1 Gtoe = 6.84 Billion bbls of oil)

	Conventional Oil				Unconventional Oil				Total
Region	I	II	III	IV	V	VI	VII	VIII	I-VI
NAM	8.5	8.6	6.7	15.9	7.6	98.8	172.8	287.4	606
LAM	17.4	8.9	15.5	18.9	2.6	91.5	160.1	270.8	586
WEU	5.6	2.1	3.6	5.1	1.3	7.6	13.3	34.6	73
EEU	0.3	0.2	0.6	0.7	0.0	0.5	1.0	3.8	7
FSU	17.1	13.6	19.3	23.4	3.3	19.4	34.0	125.6	256
MEA	87.9	17.0	21.9	56.2	22.3	39.6	69.3	279.0	593
AFR	4.0	3.4	4.9	5.4	1.4	5.1	8.9	29.7	63
CPA	5.1	4.7	8.2	7.4	2.3	42.2	73.8	118.7	262
PAO	0.4	0.3	0.6	0.7	3.7	25.8	45.1	60.3	137
PAS	2.9	1.6	2.5	3.4	0.6	4.8	8.3	23.0	47
SAS	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.

(1) Even estimates of proved reserves are likely inflated. Estimates of proved reserves are usually accepted at face value, but reserve estimates by OPEC members are likely inflated. Since reserves confer bargaining power in negotiating production quotas within OPEC, states have an incentive to inflate their proved reserve estimates to gain better bargaining positions. Campbell (1997) has estimated the overstatement of world proved reserves at about 360 billion barrels (about 35 percent).

(2) Historically, reserve growth is more a result of poor initial estimates of field size rather than technological advances in recovery methods. Geology is much more important than technology in determining recovery rates. Estimates of resources that have been made correctly will have very modest reserve growth.

(3) USGS estimates of reserve growth were further biased upwards by assuming that the rest of the world's reserve estimates were comparable to U.S. reserve estimates and that U.S. reserve expansion could be applied to the rest of the world's estimates. Since the rest of the world lists as proven what the United States would consider proven plus probable reserves, applying U.S. reserve expansion rates to other countries proven reserve estimates will result in inflated projections.

These less optimistic assessments put ultimately recoverable oil resources at a lower level (Table 3). Minimum, mean and maximum estimates for conventional oil are 1.7, 1.8 and 2.2 trillion barrels, respectively (Laherrere, 2001). These compare with USGS 2000 estimates of 2.2, 2.9, 3.9 trillion barrels. Also provided by Laherrere are estimates of unconventional oil resources that are an alternative to Rogner's estimates. Needless to say, others disagree with the less optimistic view, partly because they do not accept the critique of their estimates, and also on the grounds that past estimates, which have also had shortcomings, have consistently underestimated the world's oil resources.

Table 3. Estimates of World Conventional and Unconventional Oil Resources by Laherrere

Resource type	Minimum	Mean	Maximum
Conventional Oil	1,700	1,800	2,200
Conventional Gas Liquids	200	250	400
Non-conventional Liquids	300	700	1,500
Ultimate Liquids (Billion barrels)	2,300	2,750	4,000

Source: Laherrere, 2001, p. 62.

In the analysis below, all three sets of estimates are used: (1) USGS 2000, (2) Rogner, and (3) Laherrere. The USGS estimates are available by country, which allowed them to be rearranged into Rogner's regions, producing comparable regional estimates. Laherrere (2001) does not provide regional estimates, so his regional estimates were allocated to regions in the same *proportions* as the USGS estimates. To subdivide Laherrere's estimates into Rogner's categories, the following procedures were used. Mean conventional oil minus cumulative production to date was divided between proved reserves (I) and estimated additional reserves (II), in proportion to the USGS estimates for these categories. An estimate of speculative resources was created from Laherrere's estimates by subtracting his mean estimate from his maximum estimate (2,200-1,800 = 400 billion barrels). Finally, enhanced recovery was set to zero, on the grounds that this potential is already included in Laherrere's other estimates. Laherrere's mean estimate of non-conventional liquids was divided between categories V and VI in proportion to Rogner's estimates. This procedure will admittedly not be consistent with Laherrere's underlying detailed estimates. However, those detailed estimates are not available at this time, and the approximation does provide world totals consistent with Laherrere's assessment in the same world energy scenarios and modeling framework as used with the other assessments.

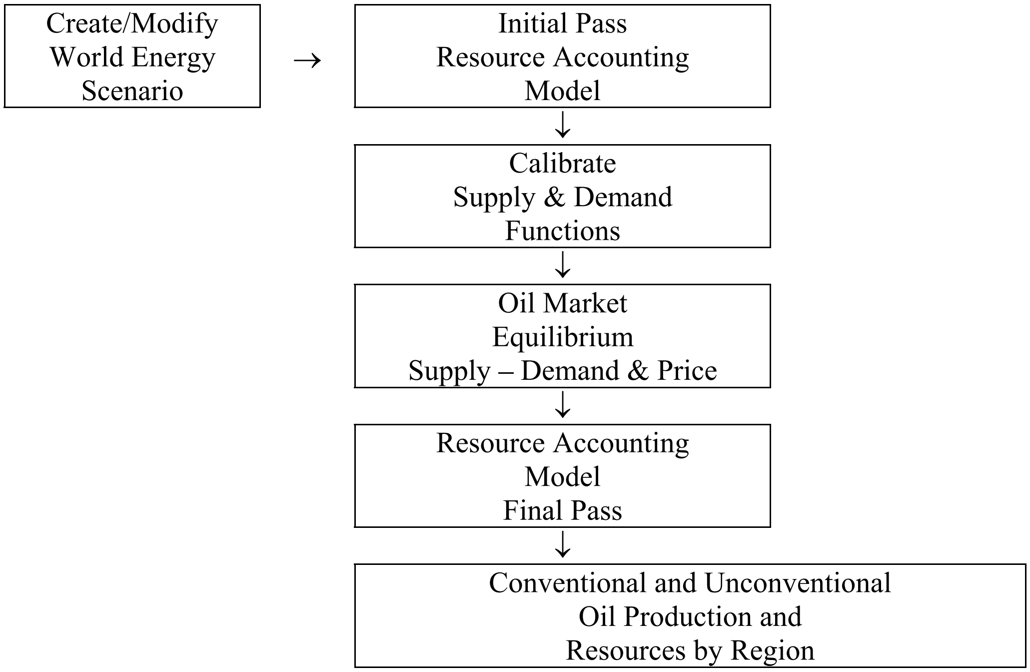
3. MODELING OF OIL DEPLETION

A parametric depletion model named the World Energy Scenarios Model (WESM) has been developed to reveal the implications of alternative world energy scenarios for the depletion of conventional oil and likely transition to unconventional oil. The model takes a given scenario of world oil use as a starting point, calibrates world oil supply and demand to the scenario using 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 passed to a resource accounting model to track depletion of conventional oil and the transition to unconventional resources (Figure 2). Details are provided in the appendix.

The WESM model has been designed to use the world energy scenarios created by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) through 2050 (Nakicenovich et al., 1998). WESM can also calibrate a IIASA/WEC scenario to match a U.S. Department of Energy International Energy Outlook 2002 projection to the year 2020 (U.S. DOE/EIA, 2001). Beyond that point it trends all variables back towards the original IIASA/WEC scenario. For North America, WESM can be calibrated to detailed transportation energy forecasts developed using the Champagne Model (NRCanada, 2002). Details of how these calibrations are accomplished can be found in the appendix.

WESM initially attempts to follow a scenario's proposed production schedule, and will deviate from it only if the economics of resource depletion so indicate. Because of this, regional and even world production will not necessarily peak at the point where 50 percent of ultimate resources have been produced. Production will eventually decline, however, as regions exhaust their ultimate stocks of oil resources. This approach is not likely to satisfy advocates of the Hubbert theory, who may point out that it will not be possible for regions to continue increasing production, or even hold it constant beyond the 50 percent depletion point (e.g., Bentley, et al., 2000). Of course, others would argue that the Hubbert theory is overly mechanistic and that if peaking ever occurs it will be determined more by economics and technology than geology (e.g., Odell, 1999). The position taken here is that this argument is unresolved, and that both schools of thought have merit. However, if the Hubbert school is proven correct, then the depletion-driven peaking times calculated by this model will occur *later* than reality would permit.

Figure 2. Flow Diagram of World Energy Scenarios Model



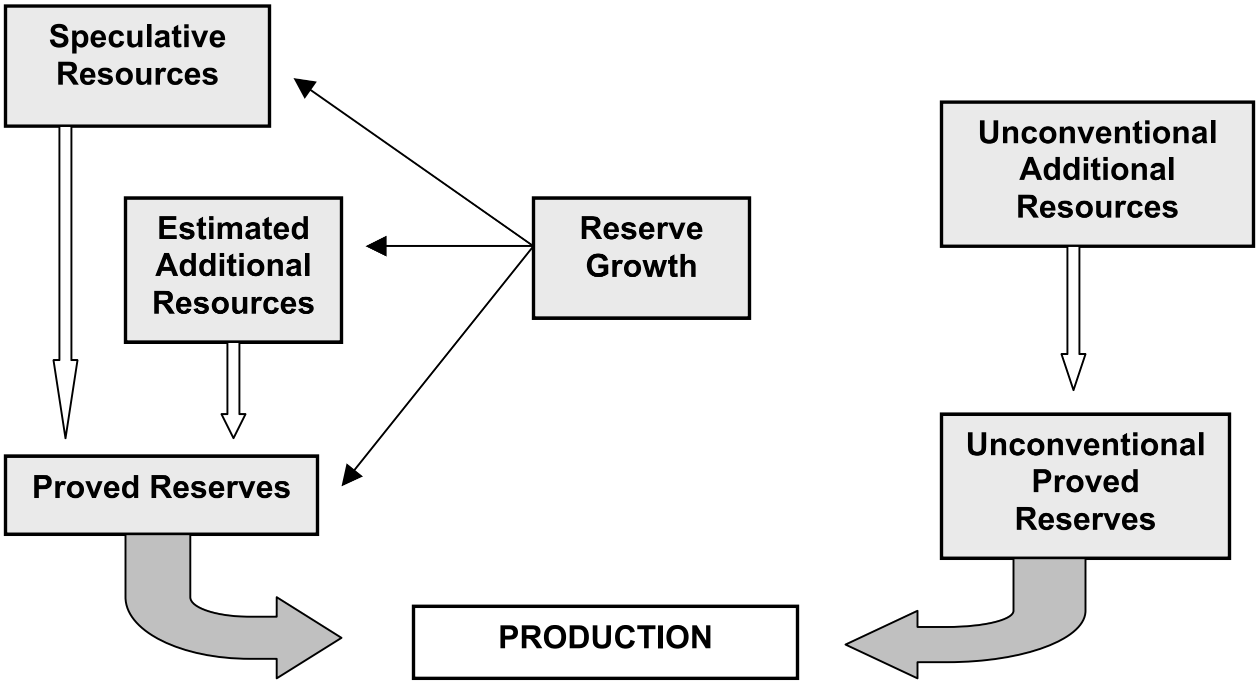
The method by which the draw down of oil resources and the transition to unconventional oil is simulated consists of two major components: (1) a set of resource depletion rules, and (2) a long-run representation of world oil market behavior consistent with the scenario in question. The IIASA/WEC scenarios specify, by region, initial estimates of both oil consumption and oil production. The resource depletion rules control what amount of conventional oil comes from which resource category, and initial estimates of when unconventional oil resources will be drawn upon. The world oil market model determines the quantities of conventional and unconventional oil to be produced by each region. These market equilibrium estimates are iterated through the resource accounting framework a second time to produce the final resource use and depletion estimates. The key parameters of these models can be varied to test the sensitivity of outcomes to key assumptions.

3.1 RESOURCE ACCOUNTING

Resource estimates from three sources, Rogner (1997), USGS (2000) and Laherrere (2001), were organized according to Rogner's first six categories. Accounting rules were then specified to determine how each type of resource would be called upon to meet the demands of the world energy scenarios.

The first principle of the resource accounting rules is that proved reserves are a stock from which current production is drawn and to which additions are made from unproved resources (Figure 3). 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. The test of whether reserves are adequate is whether the ratio of reserves to the production requirement exceeds a specified minimum reserves-to-production (R/P) ratio. The R/P ratio assumed for the analyses below is 15, but a user-specified alternative may be substituted. If the R/P ratio falls below 15, 1/15 of the required production will be taken from proved reserves.

Figure 3. Structure of Resource Accounting Model



Withdrawals from proved reserves are primarily replenished by flows from estimated additional reserves to proved reserves. The ratio of inflow from estimated reserves to production from proved reserves is "user-specified;" in the analyses in this report the replenishment fraction was set at 95 percent, assuming that additional reserves are large enough to supply it. Speculative resources, if any are assumed to exist, are developed and added to proved reserves according to a user-specified Hubbert-like curve. In this report, the default assumption is that production of speculative conventional oil resources will peak in 2020.[3]

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[3] Because even speculative resources are assumed to experience reserve growth, the bell-shaped curve will be skewed, resulting in a more gradual rate of decline than rate of expansion.

All three types of conventional resources (proved, estimated additional and speculative) are assumed to expand at a user-specified annual rate, representing the combined effects of reserve growth and technological advances increasing recovery rates. The reserve growth, however, does not appear out of thin air, but must be withdrawn from category IV resources, comprising "enhanced recovery" in Rogner's data and "reserve growth" in the USGS 2000 study. This completes the accounting of conventional resources.

If the scenario calls for a region to produce more oil than its conventional oil resources can support, it is initially assumed that the deficit will be satisfied by the world's reserves of 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 come from category VI unconventional resources according to a user-specified bell-shaped curve. For the analyses described below, conversion of unconventional resources into unconventional proved reserves is assumed to peak in 2050.

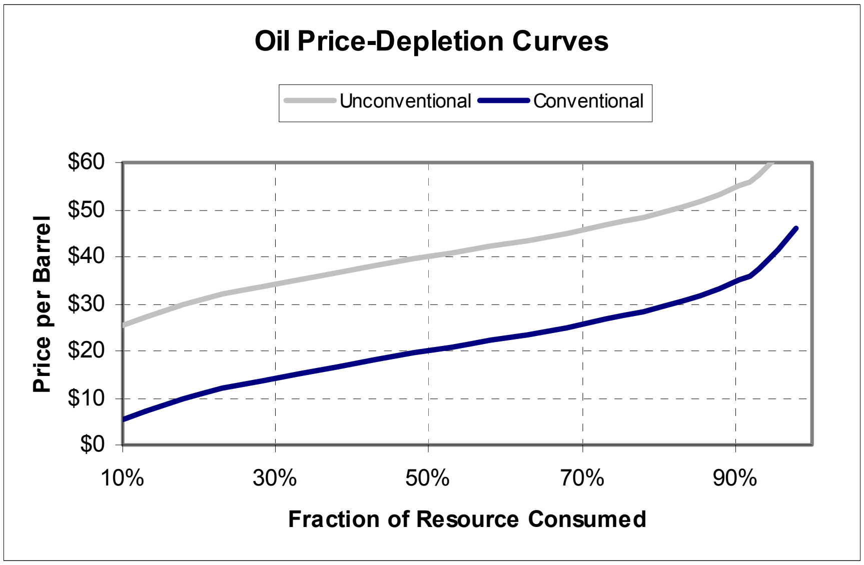
All regions' conventional oil production deficits are summed to obtain a global conventional oil production deficit. The global oil production deficit could be satisfied by either conventional or unconventional oil. Initially, all of it is allocated to unconventional oil and shared to regions according to each region's share of total unconventional resources. The final division between conventional and unconventional oil (for each region) is determined in the oil market model, based on the supply costs. If unconventional oil is expensive, some of the deficit will shift back less expensive conventional oil from regions with larger, cheaper conventional oil reserves. If world resources of unconventional oil are inadequate, the deficit is assigned to an unspecified "backstop" energy source. This is merely an accounting convenience to insure that unconventional oil stocks do not become negative.

3.2 WORLD OIL MARKET MODEL: LONG-RUN DYNAMICS

The purpose of simulating world oil market dynamics is not to predict future oil prices, but rather to represent the sensitivity of the conventional-to-unconventional oil transition to the costs of producing the two types of oil. Conventional oil production costs over the next 50 years are uncertain enough; the cost of producing unconventional oil decades in the future is still more uncertain. Little information is available on the costs of unconventional oil production by region, except for reports on Canada's Athbascan and Venezuela's Orinoco regions. Thus, the results of simulating oil market dynamics will be dependent on assumptions based on scant information. The only appropriate interpretation of the results is therefore as conditional on the assumptions made.

The simulation of world oil market dynamics begins with long-run depletion-cost curves. These logistic curves represent the cost of discovering, producing and delivering a barrel of oil to the market as a function of the state of depletion of a region's resources (Figure 4). In calculating the fraction of resources consumed, all conventional resources are counted including what has already been produced, not just proved reserves. The same applies to unconventional oil; all category V and VI resources are counted. The heights of the curves are assumed to vary by region, while the slope is the same for all regions (see appendix for details). The heights of curves may also decline over time at a user-specified rate, to represent technological progress in exploration and development. In the analysis described below, depletion cost curves are assumed to shift downward at the rate of 0.5% per year.

Figure 4.



Given the state of depletion of a region's resources entering period t, a long-run price for that region's oil is obtained from the depletion cost curve. This price, together with the initial estimate of production from the Resource Accounting Model represents a point on the region's oil supply curve. Assuming a price elasticity at that point and a dynamic adjustment rate defines a linear, lagged adjustment supply function for the region. Regional demand functions are defined in a similar way, using an initial estimate of the world oil price and the initial primary consumption of oil. The derivation of the initial price estimate is described in the appendix.

Supply functions for unconventional oil are similarly defined by the unconventional oil depletion cost and an initial estimate of the region's unconventional oil production. This estimate is supplied by the resource accounting model, described above. If a region is not capable of meeting the scenario's oil production number from its conventional reserves, the deficit becomes a world demand for unconventional oil that is shared among regions in proportion to their unconventional oil resources.

The Middle East region, comprised chiefly of OPEC members, is not represented by a supply function. Instead, its supply is treated as exogenous. Middle East oil supply is initially set by the scenario but can be changed by the model user. Both conventional and unconventional oil supply from the Middle East are treated as exogenous.

Oil demands, as well as conventional and unconventional supplies, by region, are equilibrated at a single world market price in the oil market model. Because all the supply and demand equations are linear, a closed form solution for the world oil price in each year can be calculated. This new price will shift supply between unconventional and conventional oil resources and between regions. For example, if the depletion cost of unconventional oil is high in comparison with cost of conventional oil, supply will be shifted from unconventional sources in regions lacking conventional resources to other regions with more ample conventional oil reserves. On the other hand if conventional oil becomes expensive relative to unconventional oil, production of unconventional oil will increase. Demand is also affected by oil price.

4. SCENARIOS OF WORLD ENERGY SUPPLY AND DEMAND

This section provides an illustration of the use of the model. The purpose of this exercise is to combine a variety of estimates of world oil resources with alternative scenarios of world energy use, in order to explore the times and rates of possible transitions from conventional to unconventional oil resources. The three sources of world oil resource estimates have been reviewed above. World energy use scenarios were borrowed from the IIASA/WEC study, *Global Energy Perspectives*, (Nakicenovic et al., 1998) and from forecasts of international energy use to 2020 by the U.S. Energy Information Administration (U.S. DOE/EIA, 2002). For North American transportation energy use, scenarios developed by the U.S. DOE and NRCanada were adopted (citation?). Two IIASA/WEC scenarios were 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" (Nakicenovic, 1998, p. 8). (2) Case C1, a variant of the "ecologically driven" scenario in which unprecedented international cooperation to protect the environment results in large increases in energy efficiency and renewable energy use, but little adoption of nuclear energy. While these scenarios were developed all the way to 2100, only the portions up to 2050 are used here.

In both scenarios, world population grows from 5.3 billion in 1990 to 10.1 billion by 2050 (Table 4). Gross world product (GWP) increases from $20 trillion (1990 US$) in 1990 fivefold 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. For the customized scenarios presented below, the rates of energy intensity decline were reduced by 0.2% to –0.7% and –1.2%, respectively, for the A and C scenarios. Oil use grows at a slightly slower rate than total energy in the A scenario, and in the C scenario oil use increases modestly, then falls back to its 1990 level by 2050.

Developed from a base of 1990, the IIASA/WEC scenarios are already out of synch with actual year 2000 energy consumption and production. This is particularly true of the C1 scenario, but even the A1 scenario anticipated much lower petroleum use (especially in North America). To calibrate the scenarios to actual 2000 data, and in order to substitute a more "conventional" view of the evolution of world energy markets through 2020, the scenarios were adjusted to match 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 matched to that projection through 2020. The C1 scenario was calibrated to the AEO 2002 "Low Growth" projection. After 2020, a splining method (see appendix for details) was used to trend the projections back towards the appropriate IIASA/WEC scenario.

Table 4. IIASA/WEC Global Energy Scenarios

		High Growth, A	Ecologically Driven, C
Population (billions)			
	1990	5.3	5.3
	2050	10.1	10.1
Gross World Product (trillion 1990 US$)			
	1990	20	20
	2050	100	75
Primary energy intensity improvement (%/year)			
	1990 to 2050	-0.9%	-1.4%
Primary energy demand (Gtoe)			
	1990	9	9
	2050	25	14
Oil, primary energy use (Gtoe)			
	1990	3	3
	2050	8	3

Source: Nakicenovic et al., 1998, tables 2.1 and 5.1.

In the IEO 2002 Reference Case, world energy use increases from 8.7 Gtoe (346.2 quads, at 39.68 quads/Gtoe) in 1990, to 9.6 Gtoe in 1999 and 15.4 Gtoe by 2020 (U.S.DOE/EIA, 2002, table A1). Most of the growth is projected to be in the developing countries, where energy use increases from 2000-2020 at an average annual rate of 3.7 percent. This is 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 percent, 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.

The patterns of energy production from 2000 to 2050 in the IIASA/WEC scenarios adjusted to the IEO 2002 projections and Champagne North American transportation scenarios are shown in Figure 5 for scenario A1 and Figure 6 for scenario C1.

The two scenarios were combined with the three alternative assumptions about oil resource availability, to produce six cases (Table 5). Versions of two of these cases were further analyzed to determine the sensitivity of results to two key assumptions: (1) the rate of reserve growth/enhanced recovery advances over time, and (2) the quantities and rates of development of speculative resources and unconventional resources.

The High Resources variant uses the higher USGS conventional oil resource estimates. It further assumes that fully 90 percent of speculative resources will be developed. Recall that the speculative resources are defined as the difference between the USGS median and 5th percentile estimates. The statistically "expected" amount of speculative resources would be the difference between the median estimate and the mean a far smaller amount. Additions from speculative resources to proved reserves are assumed to peak in 2020. Of the unconventional resources identified by Rogner, 95 percent are assumed to be recoverable, and transfers from unconventional resources to unconventional reserves are assumed to peak in 2050. Reserves are assumed to expand due to reserve growth and enhanced recovery at a relatively high rate of 1 percent per year (Davies and Weston, 2000).

Figure 5.

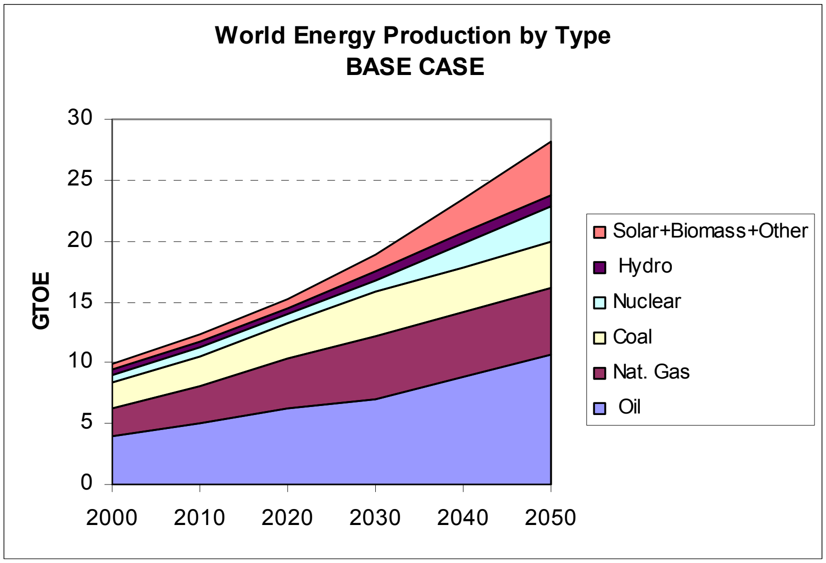


Figure 6.

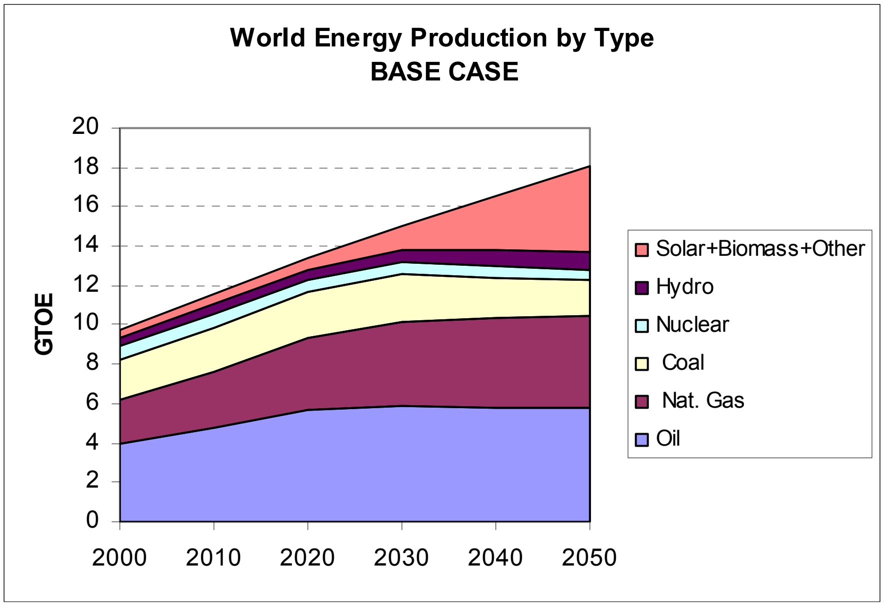


Table 5. (TITLE)

High Growth Scenario: IIASA/WEC A1 DOE/EIA IEO 2002 Reference Case			Variations run for both scenarios	Low Growth Scenario: IIASA/WEC C1 DOE/EIA IEO 2002 Low Growth Case		
Variation	Resource Estimate	Speculative Resources	Reserve Expansion	Unconventional Resources	Speculative Peak Prod.	Unconv. Peak
High	USGS	90%	1.0%/yr	95%	2020	2050
Intermediate	Rogner	50%	0.5%/yr	75%	2020	2050
Low	Laherrere	95%	0.0%/yr	99%	2015	2030

The intermediate case uses Rogner's resource estimates, and assumes that 50 percent of speculative and 75 percent of estimated unconventional resources will be available. Reserve expansion is assumed to proceed at 0.5 percent per year, about twice the rate observed in the U.S. lower 48 from 1966-79 (Porter, 1995). The cumulative reserve expansion, however, cannot exceed Rogner's estimate for enhanced recovery resources. Although this case is labeled intermediate, it still reflects a certain degree of optimism about future reserves.

The Low Resources variant assumes that Laherrere's mean estimates of world oil resources are correct. Recall that in Laherrere's view, reserve expansion is already included in the resource estimates, so that the potential for further increases is set to zero. Laherrere (2001) does not provide estimates of speculative resources as distinct from estimated additional reserves. By analogy to Rogner's use of USGS estimates, it is assumed that the difference between Laherrere's maximum and mean estimates of conventional oil resources is equivalent to speculative reserves. The pessimistic case would probably be optimistic from Laherrere's perspective, in that it assumes that almost all of the speculative resources will be available. Likewise, essentially all of the estimated unconventional resources are assumed to be available. In addition, speculative resources and unconventional resources are brought on line sooner. Even with these assumptions, it turns out that the sum total of all oil resources are not adequate for the next 50 years under the high growth scenario.

5. RESULTS

The six variants of the High and Low-growth scenarios produce a wide array of patterns of conventional oil production and transitions to unconventional oil. In all six cases a transition to unconventional oil begins well before 2050.

High Growth, High Oil Resources

In the High-High scenario, conventional oil production peaks at 126.3 million barrels per day (mmbd) in 2038 (Figure 7). Middle East (MEA) oil production, however, increases steadily throughout the period (by assumption), from 26 mmbd in 2000 to 55 mmbd in 2050. Rest of world (ROW) conventional oil production actually peaks earlier, in 2032 at 79 mmbd. Both peaks are relatively flat, so that the onset of unconventional oil production is very gradual until about 2030, when it begins to take off. From 2030 to 2050, unconventional oil output expands eight-fold, from 11 to 87 mmbd. This requires capacity to be added at a rate of about 4 mmbd each year (about 10 percent per year).

Proved reserves of conventional oil increase until 2026, at which time nearly all of the available resources of conventional oil (estimated additional, enhanced recovery and speculative) have already been converted into proved reserves (Figure 8). Total conventional oil resources decline from 3.3 trillion barrels in 2000 to 2.6 trillion in 2020, and 1.3 trillion in 2050. Over the same period, unconventional oil resources decrease only slightly from 2.5 trillion barrels to 2.2 in 2050, but there is substantial conversion from unconventional resources to reserves (again, by assumption).

Figure 7. World Oil Production

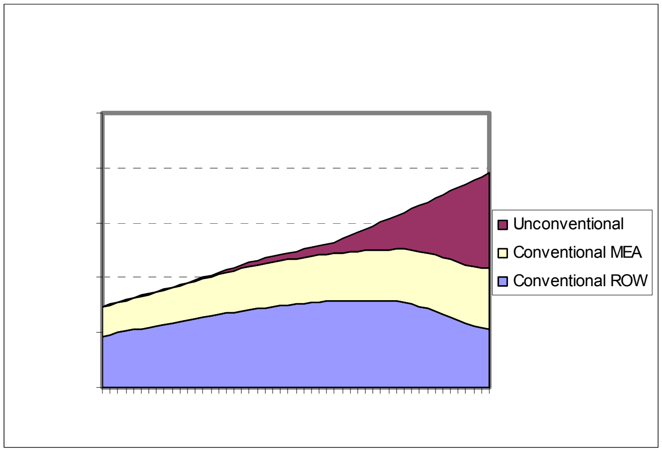
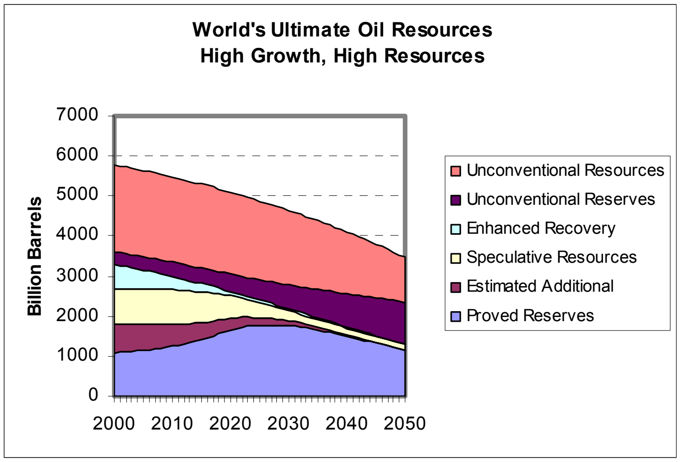
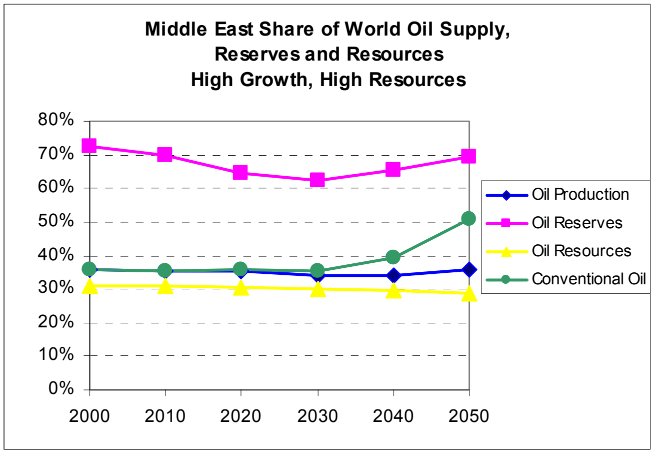


Figure 8. World Oil Resources



Despite the substantial depletion of conventional oil resources by 2050, the Middle East (MEA) shares of oil resources, reserves and of oil production are relatively steady for most of the 50-year period (Figure 9). It is important to bear in mind that MEA production is exogenous, following the IEO 2002 Reference Case projection to 2020 and trending to the IIASA/WEC A1 scenario from 2020 to 2050. There is some change in supply and demand for other regions in response to oil price changes and market equilibration. However, the MEA production share is primarily determined by scenario inputs. The key point to be taken away is that the region has the capability to maintain a position of market dominance over the entire 50-year period, even in the face of optimistic assumptions about total world conventional and unconventional oil resources. The MEA share of oil reserves dips, but is never lower than 60%; the share of total resources remains at 30% through 2050. Production is maintained at about one-third of total (conventional plus unconventional) world oil output, while the share of conventional oil output rises sharply after 2030, as the ROW runs out of conventional sources. Of course, other strategies are open to MEA producers (e.g., increase market share early on). These will be explored in future analyses.

Figure 9. Middle East Oil Shares



North American (U.S. plus Canada) conventional oil production rises very slightly through 2015 and peaks at 12.4 mmbd, after which time it begins a steep decline. Unconventional oil production expands gradually through 2030, and then grows explosively (Figure 10). This expansion is driven by world needs for unconventional oil rather than North American needs. From 2030 to 2050, North America unconventional oil production increases from 3 to 24 mmbd. By 2050, North America is producing more than one fourth of total world unconventional oil supply. Although the model does not distinguish among countries within a region, the unconventional oil supply would unquestionably be coming from Canada and not the U.S., since oil shale has not been included among unconventional oil resources. Thus, while the explosion of unconventional oil output rapidly diminishes North American dependence on oil imports, U.S. dependence is undoubtedly higher than ever (Figure 11). One key issue raised by this result is whether there is a way for U.S. energy security to be improved by Canadian production of unconventional oil in a way that results in a win-win for both countries, or whether this syncrude will simply add to the pool of world oil supply. Another is whether it would be beneficial to either country for Canadian production to begin a significant expansion at an earlier date in order to reduce dependence on Middle East oil supplies. Again, these questions are left for future analysis.

Figure 10. North American Oil Production

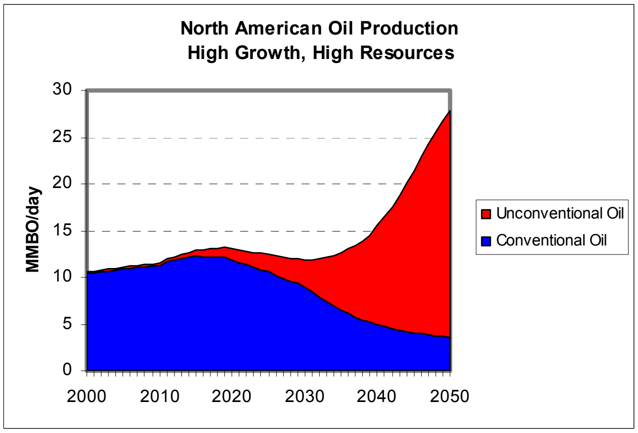
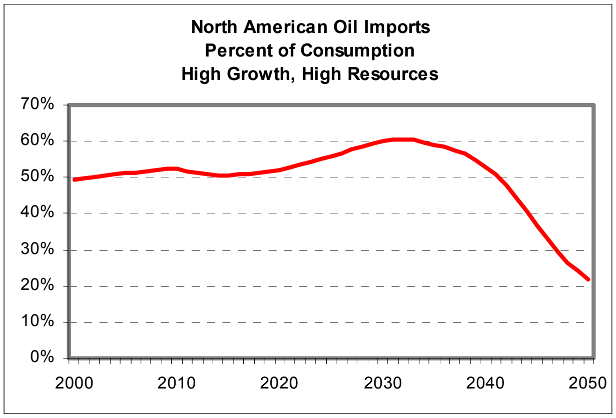
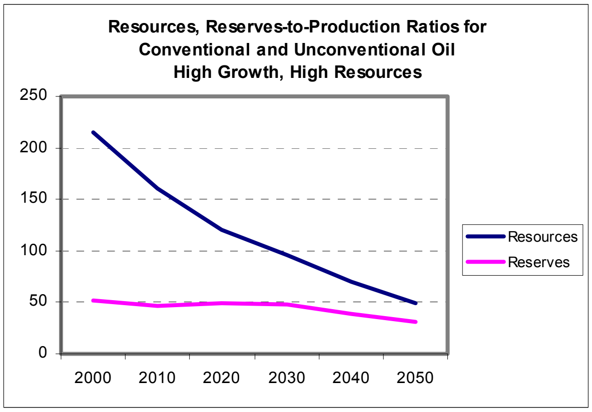


Figure 11. NA Oil Import Dependence



Resource to production ratios decline steadily through 2050, with reserve growth, even at 1%/year being unable to keep up with consumption. Reserve-to-production ratios are maintained at approximately 50 until about 2030, at which point they decline as many regions are running out both types of oil resources. More importantly, the two ratios converge, indicating that all available resources are being converted into reserves. By 2050, the total world oil resources to production ratio reach 50. If energy sustainability is defined as expanding energy resources as quickly as they are consumed so that resources for future generations are not diminished, this pattern would appear on its face not to be sustainable. However, this analysis looks at one type of resource only, namely petroleum. If new types of resources are being created to replace petroleum fuels at the same or faster rate than oil resources are depleted, then even this pattern could be sustainable.

Figure 12. World Oil R/P Ratios

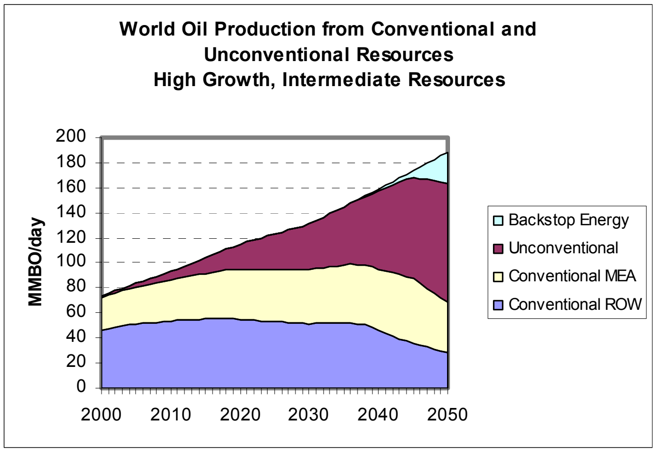


High Growth, Intermediate Oil Resources

In the high-intermediate case, conventional oil resources are more limited (according to Rogner (1997) and by assumption), and so the world must move massively towards unconventional oil to maintain the growth of oil use. World conventional oil production peaks in 2036 at 99 mmbd, but has been nearly flat for the previous twenty years (Figure 13). Non-MEA, ROW production peaks much earlier in 2020 at 55 mmbd. Reserve growth and additions from speculative reserves help sustain production during this long period of nearly constant production despite continued resource depletion. The relatively slower pace of reserve expansion in this variant leaves approximately half of the oil ultimately available for enhanced recovery still in the ground in 2050. It is not developed quickly enough to prevent conventional oil production from declining.

At the same time, even category V and VI unconventional oil resources (75% of which are assumed to be recoverable in this case) are inadequate to meet growing demand for oil before 2050. A backstop source of energy must be found, possibly in category VII or VIII resources, or some other fossil, nuclear or renewable source. This backstop comes on rapidly, growing from nothing to 25 mmbd oil equivalent in a ten year period.

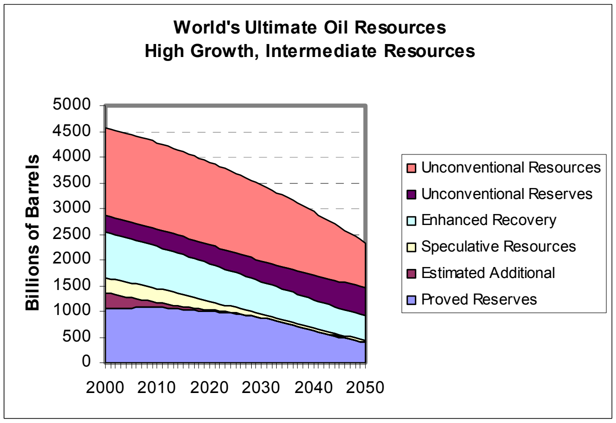
Figure 13. World Oil Production, High-Intermediate Case



This raises the potentially serious question of whether world energy markets will be able to respond quickly enough. This is not a trivial question, since the onset of declining production is rather sudden. Would prices rise to signal the oncoming peaking of conventional + unconventional oil? Would producers see the signs in declining R/P ratios? More will be said about this in the following case, where the need for backstop energy is far greater.

In the high-intermediate case, proved reserves of conventional oil peak in 2008, followed by a very gradual decline through 2030, accelerating afterwards (Figure 14).

Figure 14. Ultimate Oil Resources, High Growth/Intermediate Resources



World combined conventional and unconventional reserves-to-production ratios decline steadily from 50 in 2000 to 15 in 2050 (Figure 15). Total resources-to-production declines from 167 to 31. In this scenario, the world is beginning to run out of oil by 2050.

With conventional oil production virtually flat from 2025 onward, the world's growing oil demand is met by unconventional oil resources and, ultimately, by backstop energy. From 6.5 mmbd in 2010, unconventional oil production increases to 95 mmbd in 2050. In North America, unconventional oil production begins to ramp up after 2010 and skyrockets after 2020. By 2050, North America produces 24 mmbd of unconventional oil plus 3 mmbd of conventional oil (Figure 16). As a result of the explosive growth of unconventional oil production, NAM actually becomes a net exporter of oil in 2050 (Figure 17). Again, virtually all of this is due to increased Canadian output of unconventional oil. U.S. oil imports would be nearly 100%.

Figure 15. R/P Ratios, High Growth/Intermediate Resources

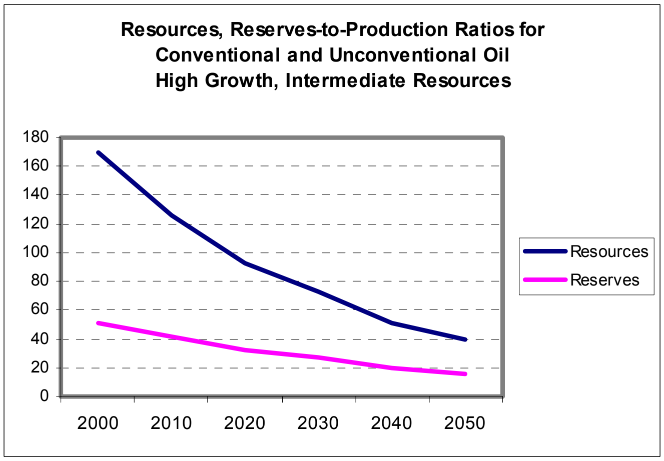


Figure 16. NAM Oil Production, High Growth/Intermediate Resources

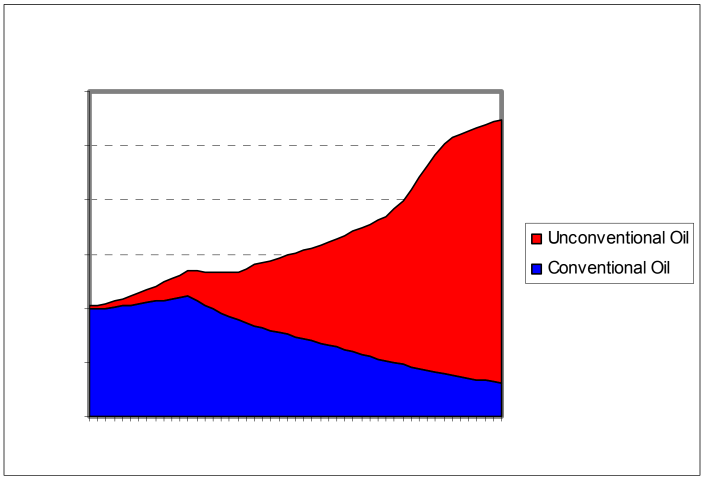
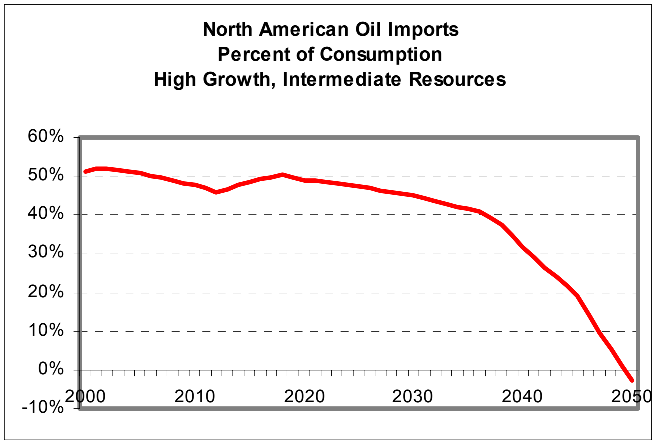


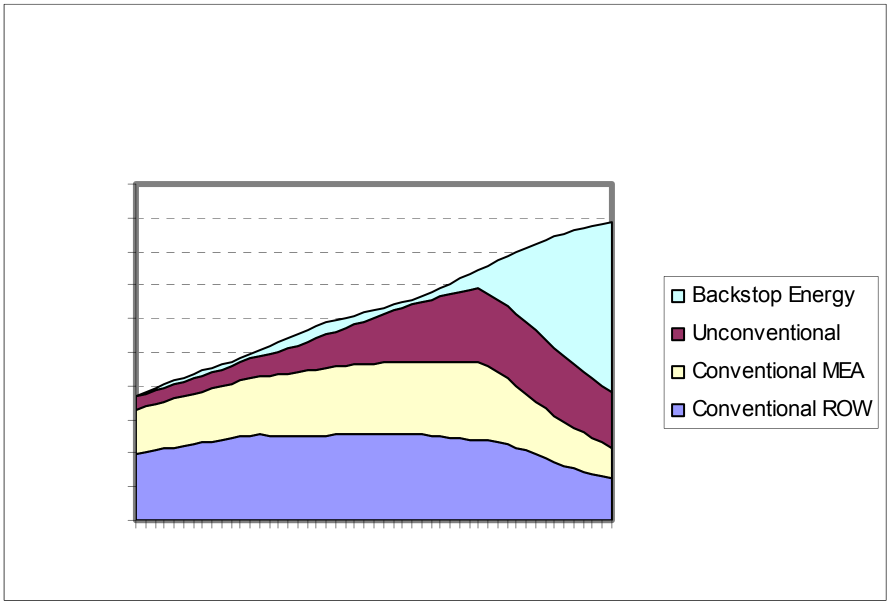
Figure 17. NAM Oil Imports, High Growth/Intermediate Resources



High Growth, Low Oil resources

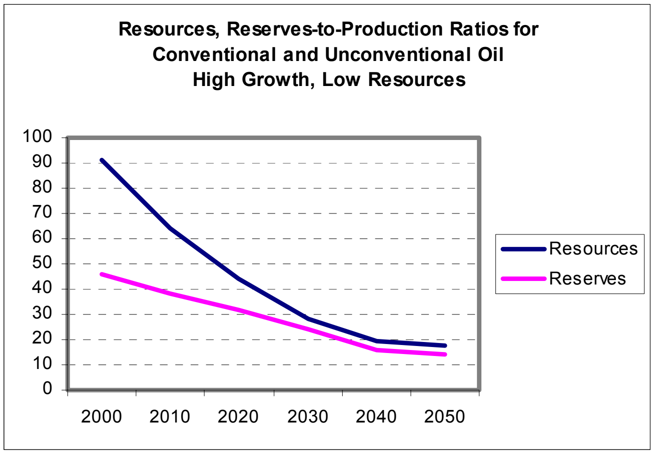
Given the less optimistic assumptions about world oil resources of Laherrere (2001), the high growth oil consumption trajectory ends in 2037. At that point, the world effectively "runs out" of both conventional and unconventional oil. Conventional world oil production literally peaks in 2029 at 94 mmbd, but it becomes severely constrained 2013 when non-MEA oil output hits 51 mmbd (Figure 18). ROW oil production remains essentially constant until decline sets in after 2030. The need for unconventional oil is immediate in the high-low case, since some regions cannot produce what the scenario requires in 2000. Output of unconventional oil increases quickly, but with only 700 billion barrels total resources of unconventional oil (about 100 Gtoe), all of the world's oil resources are inadequate to supply the scenario's demands through 2050. Between 2036 and 2050 100 mmbd of backstop capacity must be introduced to meet the scenario's demand for oil. Will this be feasible? Will the world see it coming and create a more gradual transition?

Figure 18. World Oil Production, High Growth/Low Resources



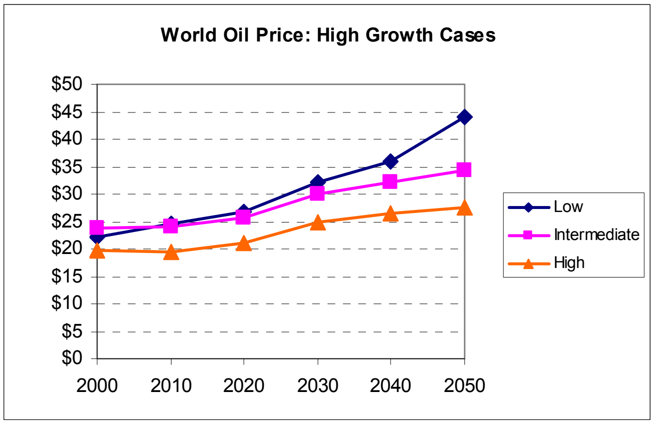
Whether the world economy would sense the depletion of oil resources and respond accordingly may be a very important question. Certainly, R/P ratios are far lower in this case than in the high resource case (Figure 19). About five years before the turning point in 2036, the global reserves-to-production ratio is 20, about 5 points lower than in the intermediate case, and less than half the level of the high resources case. However, the resource-to-production ratio of the intermediate case is more than twice that of the low resources case in 2030. This suggests that understanding which case the world is actually in depends more on total resource-to-production ratios than on reserve-to-production ratios. The problem with this is that there is considerably more uncertainty and disagreement about the quantity of resources than reserves. The implication is that unless we can agree on resource estimates markets will not be able to see turning points coming.

Figure 19. R/P Ratios, High Growth/Low Resources



The most critical indicator for the market would be the price of oil (Figure 20). While WESM calculates world oil prices, they simply reflect the user's assumptions about cost-depletion relationships and rates of technological progress. Relative prices from different cases reflect slower rates of depletion, since the same depletion-cost curves and rate of technological progress in oil supply was assumed for all cases. Conditional on all of this, differences between the Low and intermediate resource cases are quite small until after 2030, suggesting that production cost alone might not signal a turning point. Of course, if analysts anticipated such a turning point and the owners of oil resources were convinced it was coming, a Hotelling resource scarcity effect might increase the price differences beyond what is seen here. In any case, these price forecasts should be considered highly uncertain and interpreted accordingly.

Figure 20. World Oil Prices in the Three High Growth Cases



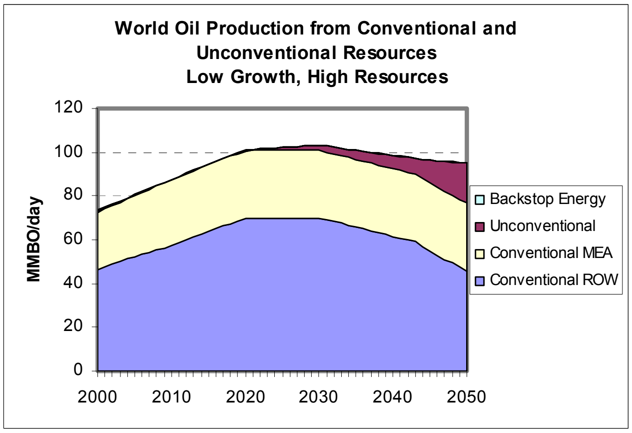
It is interesting that those who argue that "running out" of oil is not now and never will be a problem believe that to be so because markets and human intelligence will solve the problem before it arises. This would require either that the world saw the crunch coming and acted on the foresight, or that technological ingenuity advanced so rapidly that the problem never arose. The latter may be the most likely outcome, but is it prudent to plan on only that possibility? Moreover, if one is convinced that human ingenuity will solve the problem, how could one insure that the world saw it coming?

Low Energy Demand Growth, High Resources

The Low Energy Demand scenario was based on the IIASA/WEC C1 Scenario and the IEO 2002 Low Economic Growth Projection, modified so that OPEC production reaches 1.65 Gtoe in 2020 and remains there until 2050. The case contains few surprises. There is plenty of oil and the world needs less of it. Total world oil use grows from 73 mmbd in 2000 to 101 mmbd in 2020 but then falls back to 95 mmbd by 2050. The peaking of oil use is caused by calibration to the IEO 2002, which even in the Low Economic Growth Projection foresees oil demand increasing through 2020. The scenario then trends back toward the more aggressively low oil demand C1 Scenario. Ironically, oil use does peak in this scenario (Figure 21) but not because of oil depletion. Analogously to the "Stone Age ending but not for lack of stones," the oil age ends as economies move to renewable energy and efficient technologies in the presence of abundant oil supplies.

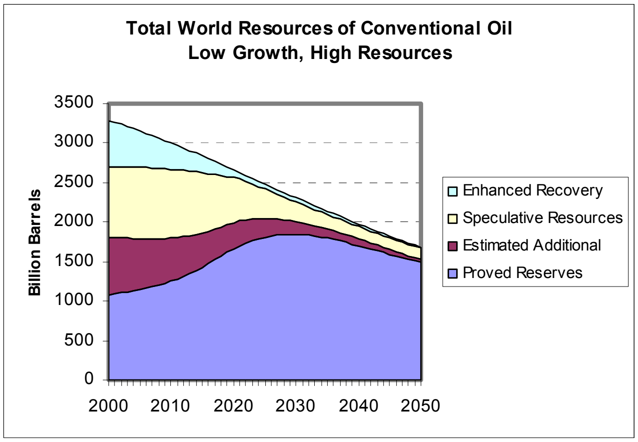
With plenty of oil, there is no need for a backstop energy source, and little need for unconventional oil. Even in 2050, only 14 of the worlds 87 mmbd of oil production come from unconventional sources. One may wonder why any unconventional oil is used at all. Even with supplies abundant globally, some regions deplete their conventional resources, North America being one. Because of the assumed technologically driven decline in unconventional oil production costs, unconventional NA oil becomes increasingly competitive with conventional oil from other regions toward the second half of the period.

Figure 21. World Oil Production, Low Growth/High Resources



The continuing depletion of conventional oil resources even with much-reduced rates of consumption is illustrated in Figure 22. Proved reserves peak in 2029 at 1.8 trillion barrels, and by 2050 nearly all of the available resources of conventional oil have been converted to proved reserves.

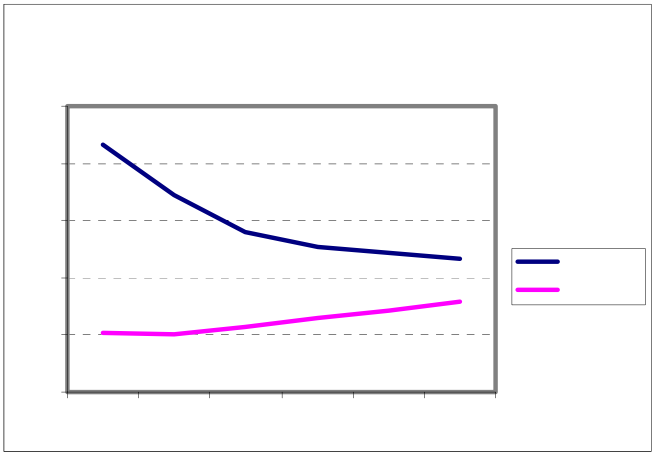
Figure 22. World Conventional Oil Resources: Low Growth/High Resources



The oil market share of the Middle East region falls from 36% in 2000 to 31% in 2020, and then rebounds to 40% by 2050 as MEA production remains constant (by assumption) while ROW world production falls. Clearly, the region has the potential to seize a greater share of the market at an earlier date, but not without further undermining oil prices, which remain below $20/bbl until almost 2020, and then gradually increase to $35/bbl. Oil prices increase despite assumed reductions of 0.5% per year in the cost of oil production because ROW depletion is outpacing that rate, eventually requiring a shift to unconventional oil. And although unconventional oil costs are also declining, they are not declining fast enough (also 0.5% per year) to entirely offset the effect of the depletion of conventional oil.

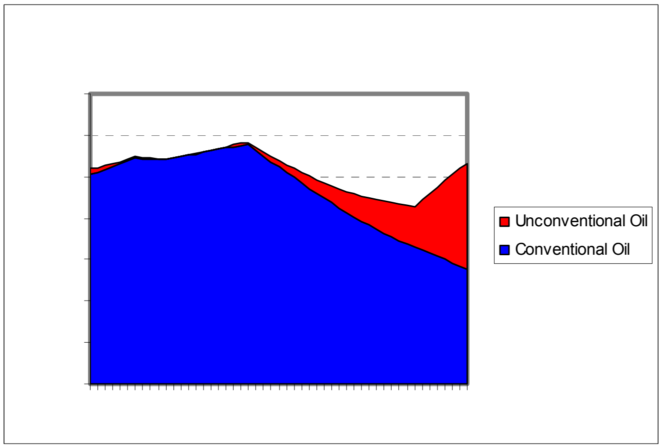
Perhaps the most interesting outcome of this scenario is found in the R/P ratios. Unlike all the other scenarios R/P do not fall continuously. Instead, the Reserves-to-Production ratio increases over time as unconventional oil resources are converted to reserves (by assumption) while production eventually declines. The Resources-to-Production ratio appears to stabilize at a comfortable level of about 115 (Figure 23). The stabilization of the resource-to-production ratio could be interpreted as an indicator of a sustainable energy situation: the expansion of resources approximately equals their consumption. Of course, this considers only one type of energy, and technological advances may have been making other types viable, as well.

Figure 23. R/P Ratios, Low Growth/High Resources Case



North American oil imports rise gradually to 57% by 2020, then increase to the vicinity of 70% after 2030 and remain there until almost 2050. The import share is not significantly reduced because there is little call on unconventional oil until very late. However, after 2044, unconventional oil production increases rapidly (Figure 24).

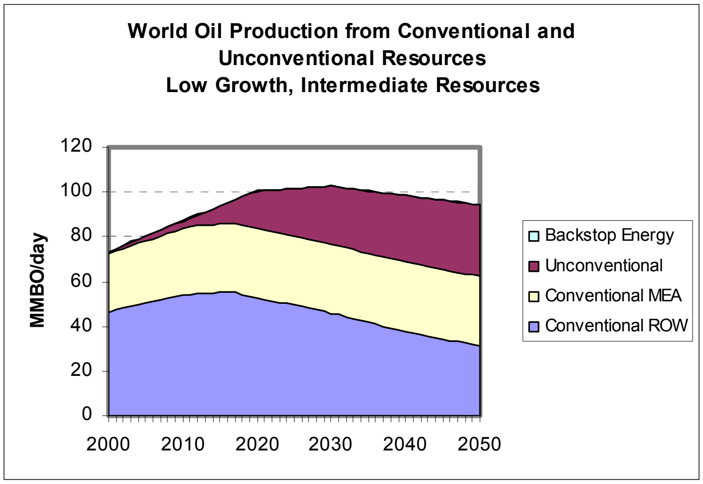
Figure 24. North American Oil Production, Low Growth/High Resources



Low Energy Demand, Intermediate Resources

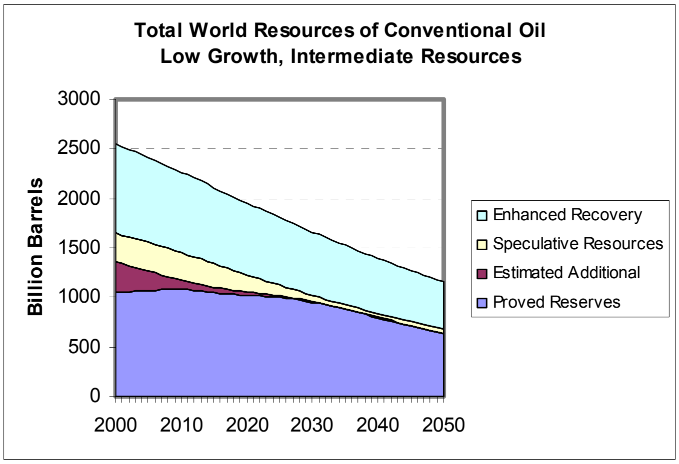
In the intermediate resource case of the low energy demand scenario, non-MEA conventional oil production peaks in 2016 at just over 55 mmbd. World conventional oil production also peaks in this year, as MEA output is assumed to remain constant at 1.65 Gtoe from 2020 to 2050. Substantially more depletion is occurring in this case than in the High Resources case, as evidenced by the much larger contribution of unconventional oil to the global supply after 2015 (Figure 25).

Figure 25. World Oil Production: Low Growth/Intermediate Resources



Proved reserves of conventional oil actually peak in 2008, because additions from additional reserves, speculative resources and enhanced recovery are not sufficient to continue increasing reserves. In the intermediate resources case enhanced recovery expands reserves at 0.5% per year, leaving much of the conventional oil yet to be produced still in the ground in 2050 (Figure 26).

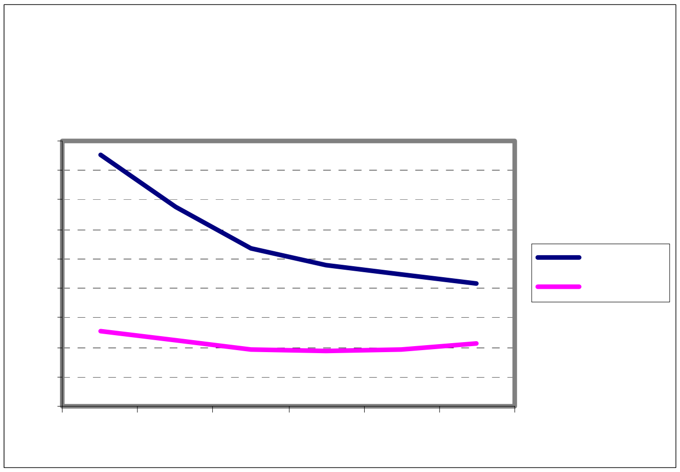
Figure 26. Conventional Oil Resources: Low Growth/Intermediate Resources



R/P ratios remain relatively high, however: about 40 for reserves and 80 for resources (Figure 27). Once again, as demand for oil declines and technological advances expand available resources, R/P ratios appear to converge toward “sustainable,” nearly constant levels.

Even with greater production of unconventional oil, NA import dependence remains high, hovering about 50% through 2020, then gradually increasing to just over 60% by 2050. Oil prices are somewhat higher in this case, as well, reflecting the greater degree of oil depletion. Starting at $23/bbl in 2000, prices increase to $29 by 2030 and then to $42/bbl in 2050.

Figure 27. R/P Ratios: Low Growth, Intermediate Resources



Low Growth, Low Resources

In the low-growth, low-resources case, depletion of conventional oil resources begins to affect supply almost immediately. World conventional oil production peaks in 2012 at 80 mmbd, just slightly higher than today’s output levels. Non-MEA production peaks in the same year at 50 mmbd (Figure 28). Unconventional oil is needed immediately, as some regions are even today not able to meet the R/P=15 assumption for proved reserves of conventional oil. There is even some initial use of “backstop” energy, as proved reserves of unconventional oil are initially insufficient to handle production requirements. These “results” must be interpreted with care, since they are largely dependent on key assumptions of the analysis, for example, that conversion of unconventional resources to reserves peaks in 2030. Overall, however, the patterns are consistent with a world in which oil resources quickly become scarce, and where even slow economic growth is not able to prevent oil supply problems before 2020. On the positive side, the reduction in oil demand after 2020 (driven by the IIASA/WEC C1 Scenario) allows time for unconventional oil resources to be developed, and the world reaches 2050 without running out of conventional plus unconventional oil.

By 2010, North American conventional oil resources are unable to support an R/P ratio of 15, and so production declines rapidly in the low-growth/low-resources case. (In reality, of course, NA production is already in decline. Supporters of the Hubbertian view would probably point to this fact as evidence that the R/P=15 assumption is not supportable and that world conventional oil production must peak sooner than implied by this case.) The inadequacy of NA conventional resources and the relative abundance of NA unconventional resources lead to a rapid expansion of unconventional oil production beginning just after 2010 (Figure 29).

Figure 28. World Oil Production: Low Growth/Low Resources

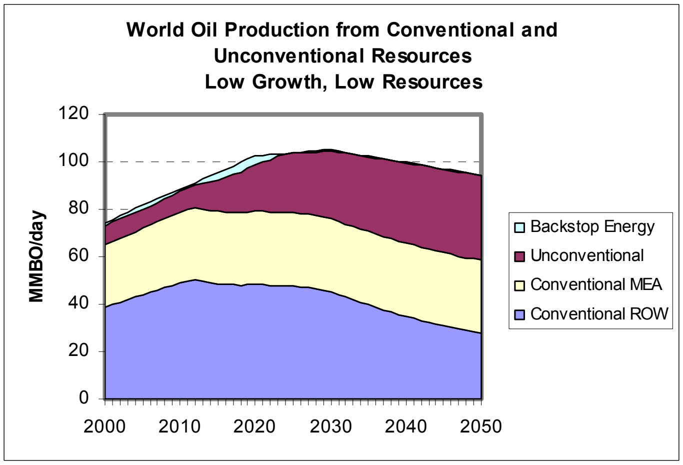
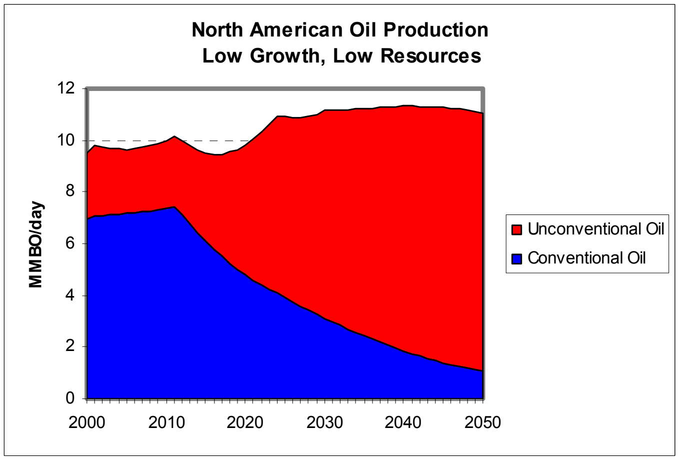


Figure 29. North American Oil Production: Low Growth/Low Resources



The expansion of NA unconventional oil production from about 2 to 10 mmbd is only a little more than enough to make up for the loss of conventional output. This, together with small increases in NA oil demand (driven by the Champagne Model predictions rather than the IIASA/WEC C1 Scenario) result in increased oil import dependence for NA through 2050 (Figure 30).

Middle East oil producers, on the other hand, are able to maintain their current level of market dominance all the way to 2050. Indeed, the MEA also remains the low cost oil producer, increasing its share of the low-cost conventional oil market from 40% to over 50% while maintaining a nearly 40% share of the total world oil market (Figure 31). It is important to keep in mind, however, that MEA production is set by assumption in this analysis, and that many alternative paths are open to MEA producers.

Figure 30. NA Oil Import Dependence: Low Growth/Low Resources

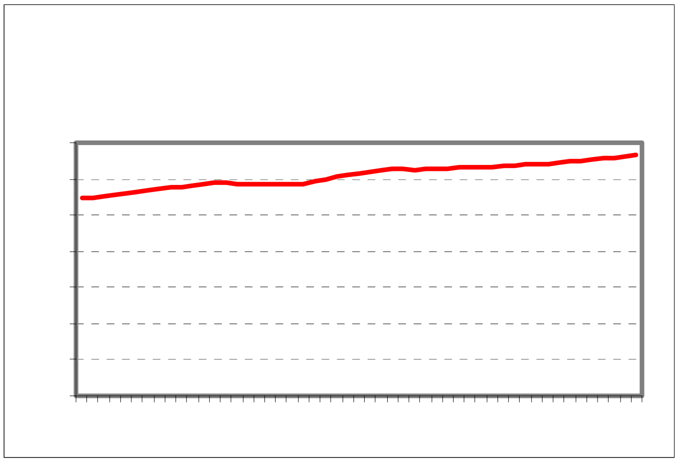
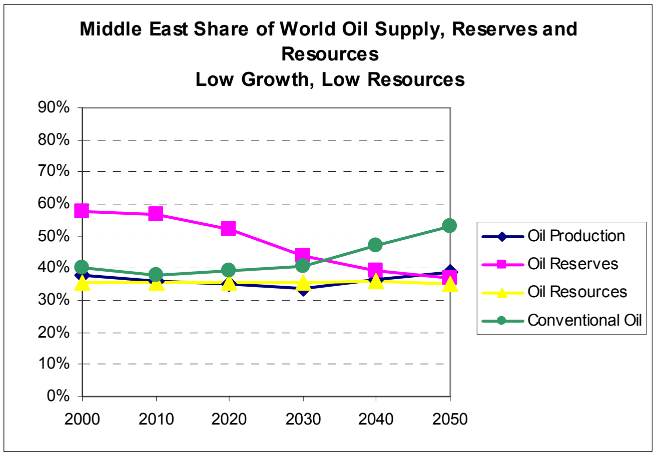


Figure 31. MEA Shares of World Oil: Low Growth/Low Resources



Sensitivity Cases

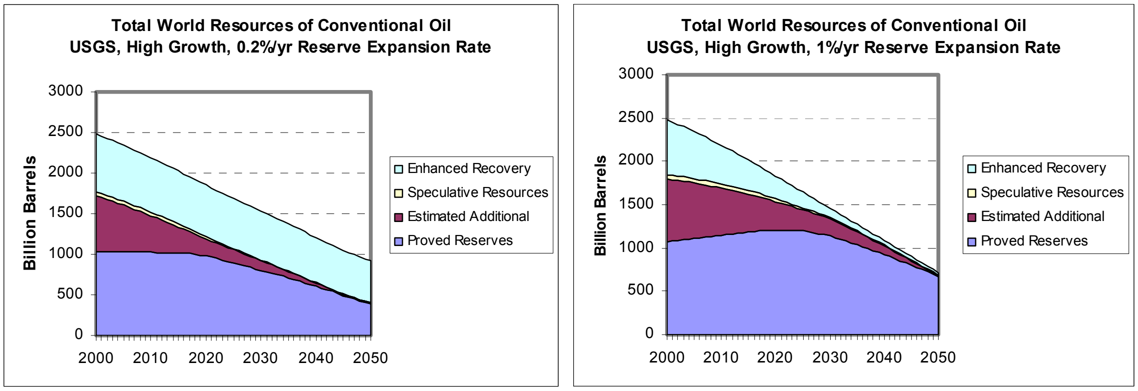
The patterns of oil depletion and transitions to unconventional oil resources illustrated in the scenarios and cases presented above are strongly dependent on a number of key assumptions. There has not yet been time for a comprehensive sensitivity analysis, yet it is important to provide at least some illustration of how plausible alternative assumptions could change the results. This section provides sensitivity tests for two key parameters under two different assumptions about oil resource availability. First, given USGS estimates of world oil resources, the impact of alternative rates of reserve growth/enhanced oil recovery on the time of peaking of conventional oil production is tested. Second, using Laherrere's estimates of oil resources, the impacts of the timing of development of speculative conventional oil resources and unconventional oil resources on peaking dates is examined. Both scenarios use the IIASA/WEC A1 Scenario combined with the IEO 2002 Reference Case and the Champagne Reference Case for North America.

Effects of Reserve Expansion Rates

This assessment was carried out using the USGS resource estimates and varying the rate of reserve expansion. A key difference between this case and the High Resources cases described above is that only 5% of the speculative resources of conventional oil are assumed to be developed. This is actually closer to the USGS mean estimate of conventional oil resources, because speculative resources are defined as the difference between the USGS 50th percentile and 5th percentile estimate. Thus, the best guess of how much of the speculative resources actually exist is close to zero.

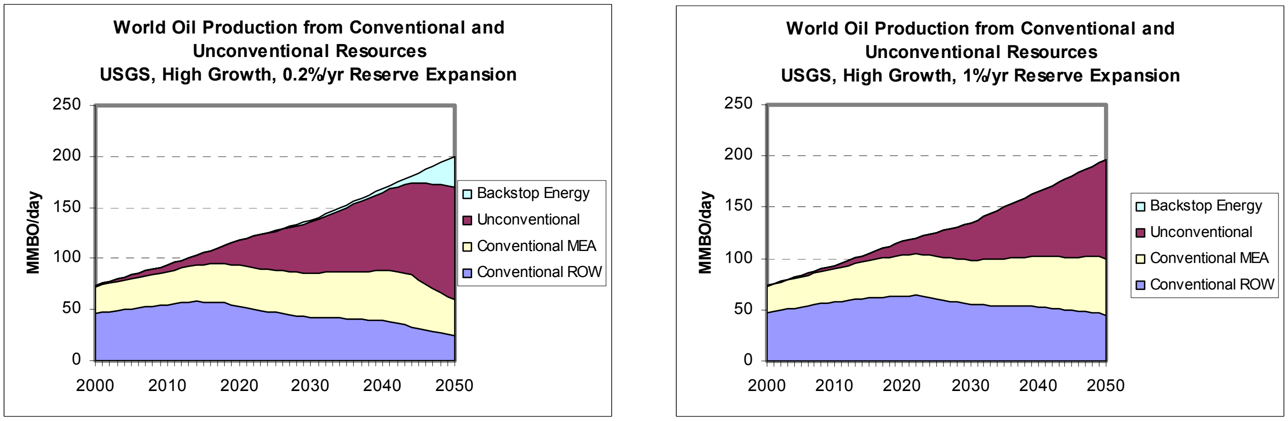
Three alternative cases are created by assuming reserve expansion rates of 0.2%, 0.5% and 1.0%, respectively. This set of values spans the range of interest. The 1% rate essentially exhausts the total amount available for reserve expansion before 2050 (Figure 32). The 0.2% growth case, on the other hand, leaves most of the potential resource in the ground in 2050 (Figure 33).

Figures 32 and 33. Conventional Oil Depletion: 1% and 0.2% Reserve Expansion Rates



Given the 0.2% reserve expansion rate, world conventional oil production peaks in 2017 at 95 mmbd. Non-MEA production peaks in 2014 at 58 mmbd (Figure 34). Assuming the 1% expansion rate pushes these dates back to 2022 for both world total and non-MEA conventional oil production, with peak rates of 105 mmbd and 64 mmbd, respectively (Figures 34 and 35).

Figures 34 and 35. World Oil Production: 0.2% and 1.0% Reserve Expansion Cases



In either case, conventional oil production is relatively flat after 2015 and unconventional oil production must be expanded at a rate equal to or greater than the rate of growth in oil consumption. In the 0.2%/yr reserve expansion case backstop energy is needed before 2050, illustrating the point that in a world of growing energy consumption it is not just the quantity of oil ultimately recoverable that matters, but how quickly it can be developed.

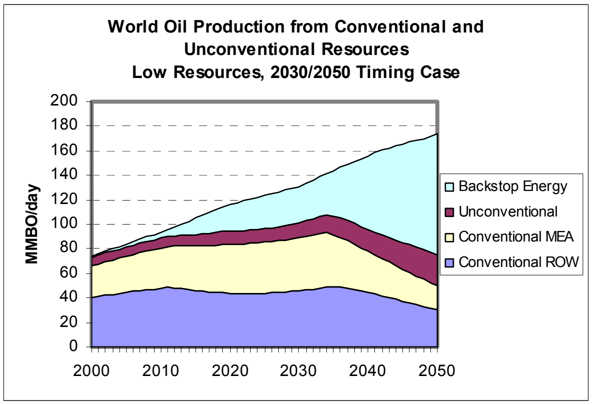
Effects of the Timing of Conversion of Resources to Reserves

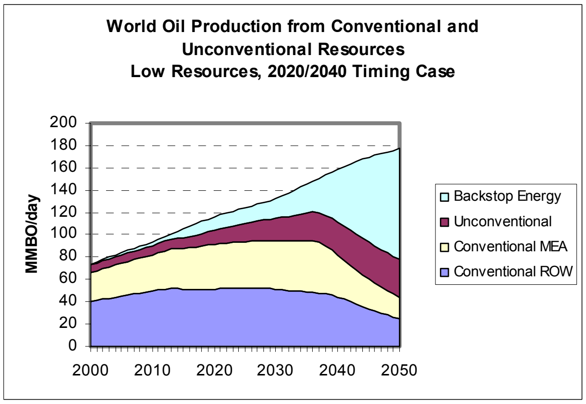
The second sensitivity analysis examines the effects of the timing of conversion of speculative conventional resources and unconventional resources to reserves. The path of conversion of these resources is described by a logistic curve for cumulative discovery, which implies a bell-shaped curve for conversion per year. The speculative resource conversion curves are somewhat skewed by reserve expansion and enhanced recovery. As shown in the appendix, the curves are determined by the ultimate size of the resource and by the year by which 50% of the resource has been converted to proved reserves.

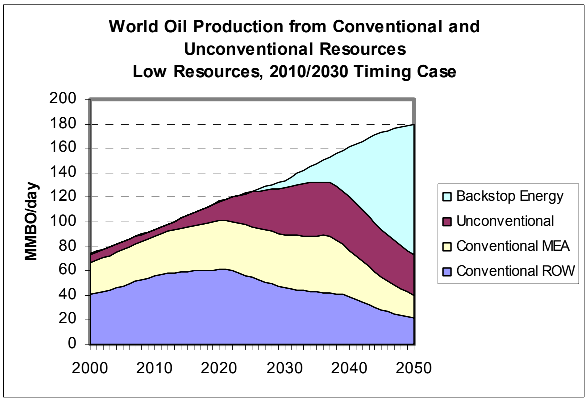
Starting with Laherrere's resource estimates, three alternative pairs of 50% dates are considered for speculative resources and unconventional resources, respectively: (1) 2030 and 2050, (2) 2020 and 2040, and (3) 2010 and 2030. Just as in the low resource case above it was assumed that 95% of possible speculative resources will be available. Ninety-five percent of Laherrere's estimates of unconventional oil resources are assumed to be available.

The principle effects of accelerating the timing of the development of speculative resources and unconventional resources are to postpone the need for backstop energy and to require that it be developed much more rapidly after 2036. With speculative resources peaking in 2030 and unconventional resources peaking in 2050, non-MEA conventional oil production peaks twice, first in 2011 at just below 49 mmbd and a second time in 2036 at just over 49 mmbd. Total world oil production slows in 2011 but does not peak until 2034, at which point even the MEA region begins to run out of oil. If these 2030/2050 results seem implausible it must be due to the delay between the peaking of non-MEA conventional oil production and the peak development of speculative resources. Surely the peaking of non-MEA oil production in 2011 would produce much higher prices signaling that every effort should be made to quickly develop speculative resources. The long-run depletion costs generated by the model, however, provide no such signal. Estimated oil prices remain at just under $24/bbl through 2010, then gradually increase to $27/bbl by 2020, and continue increasing at an accelerating rate to reach $42/bbl in 2050. Of course, these estimate a strictly dependent on many assumptions. Two key assumptions are that (unlimited) backstop energy is available at the current price of oil, and that MEA production is as shown.

Figures 36, 37 and 38. World Oil Production Under Three Scenarios of the Timing of Speculative and Unconventional Resource Conversion to Proved Reserves.







6. CONCLUSIONS

The scenario analyses of world oil depletion presented in this report are dependent on a number of critical assumptions, nearly all of which are arguable to some degree. It would therefore be an exercise of doubtful utility to attempt to present firm conclusions based on these assessments. However, several tendencies can be inferred which seem worthy of additional analysis.

If present energy use trends continue (as represented by the High Growth scenario), unless the best available estimates of world conventional and unconventional resources are very seriously in error, a transition from conventional to unconventional oil will begin before 2030. If the lower resource estimates are correct, the transition is already underway. This suggests 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.

The question of the peaking of conventional oil production appears to be a matter of when rather than if. Perhaps the most interesting result generated by the scenario analysis is that the rate of technological progress in expanding reserves and increasing recovery rates appears to be a more significant determinant of the date of peak production than the estimated amount of resources that eventually can be produced by technological progress. How fast progress occurs seems to be more important than how much progress will eventually be made.

While the price estimates presented here are highly dependent on assumptions, there is at least a suggestion that depletion costs may not provide a timely signal to markets that a turning point is imminent. This may be so for several reasons. Changes in production costs, as represented in this analysis, are very gradual until resources are nearly totally depleted. The availability of a close substitute in the form of unconventional oil also tends to moderate price increases. Technological progress may further dampen any tendency for prices to increase. Finally, although this analysis has nothing to say about this issue, short-term fluctuations in oil prices could very well obscure the long-term signal. Some may ask, so what? If prices are low, what is the problem? The problem appears to be that markets may not see potentially disruptive turning points coming. These turning points could require extremely rapid increases in the production of alternative energy sources or major reductions in demand. In the long run, markets will sort this out. However, the short-run disruptions could be very expensive.

It appears that the market dominance of Middle East oil producers is robust to a wide range of alternative demand and resource availability scenarios. This is evidenced by their ability to maintain market shares in the vicinity of 40% to 50% over the entire 50-year period in all scenarios and variants. This implies that the U.S. oil dependence problem is a long-run problem, and one that will probably require major changes in transportation technology, or energy sources for transportation, or both. The potential for unconventional oil supply from Canada may hold great promise, but only if the two countries can devise a win-win strategy for greatly expanded production. The benefits of reducing petroleum demand, per se, are not well illustrated in this analysis, since they appear to be mainly due to reducing the importance of oil as a factor in the U.S. economy, and this has not been measured. This analysis has also not explored the ability of MEA oil producers to create oil price shocks and the impacts on the U.S. economy under the different scenarios. Scenarios implying radically different energy sources for transportation (such as hydrogen) have also not yet been explored. Clearly, much analysis remains to be done.

What is clear is that it is not too soon to begin analyzing potential transitions from conventional oil and considering whether more desirable alternatives may be achievable.

APPENDIX

World Energy Scenarios Model Description

A1. OVERVIEW

A1.1 PURPOSE

The World Energy Scenarios Model (WESM) is a tool for creating global energy scenarios to 2050, and for exploring the impacts of alternative futures for North America's transportation systems in the context of those scenarios. The model focuses on world oil resources and oil markets and especially on exploring the transition from reliance on conventional oil resources to unconventional sources, such as heavy oil, tar sands and oil shale. It also tracks the depletion of world natural gas resources.

A1.2 FUNCTION

The WES Model is designed to carry out four key functions:

1. Facilitate the construction of quantitative global energy Scenarios
2. Reconcile those Scenarios with Cases of N.A. transportation energy use
3. Calculate global oil market equilibria for Scenario-Cases and,
4. Account for the depletion of oil and gas reserves and resources, by category.

While all energy types are represented, the focus is on world oil markets and oil resources in the initial version of the model. Partial equilibrium effects only are represented in the test version. This version makes no attempt to represent how the rest of the world might respond to the North American transportation cases, but rather estimates their impacts in the context of a world scenario that, with the exception of world oil markets, is fixed.

Reserve and resource accounting is the key function of the WES Model. Both conventional and unconventional resources are considered, including discovered, and estimates of undiscovered resources. Also recognized is the potential for expansion of existing and future resources due to enhanced recovery, enabled by technological advances. Both stocks and flows of resources of six different categories are tracked.

A1.3 STRUCTURE

For eleven world regions, WESM tracks energy production, primary energy use and final energy use, by energy type. Beginning with integrated world energy scenario databases created by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) (Naki□enovi□, 1998), broad patterns of energy production and use may be customized by the user. Factors that can be manipulated include, (1) rates of improvement in the energy intensities per dollar of GDP of overall primary and final energy use, (2) calibration to U.S. Department of Energy International Energy Outlook (IEO) forecasts to 2020, and (3) calibrations to Champagne model (citation?) scenarios of North American transportation use. In the future, the ability to alter the paths of energy use by individual fuel types and regions may be added. The ability to modify the WEC-IIASA scenarios is mechanistic. It is not based on energy market and macroeconomic interactions, but rather on the application of user-specified rates of change or calibration to an alternative world energy forecast. Therefore, the responsibility for the integrity of a modified scenario rests with the user.

Table A1. WEC-IIASA Scenarios

B	Middle Course
A1	High growth, Ample oil and gas
A2	High growth, Return to coal
A3	High growth, Fossil phaseout
C1	Ecologically driven, New renewables with nuclear phaseout
C2	Ecology driven, Renewables and new nuclear

Table A2. World Regions and Abbreviations

NAM	North America (USA and Canada)
WEU	Western Europe
PAO	Pacific OECD (Japan, Australia, New Zealand)
FSU	Newly independent states of the former Soviet Union
EEU	Central and Eastern Europe
LAM	Latin America and the Caribbean
MEA	Middle East and North Africa
AFR	Sub-Saharan Africa
CPA	Centrally Planned Asia and China
PAS	Other Pacific Asia
SAS	South Asia
IND	Industrialized countries (NAM, WEU, PAO)
REF	Reforming economy countries (EEU, FSU)
DEV	Developing countries (LAM, MEA, AFR,CPA, PAS, SAS)
TRD	International trade
WOR	World total

Table A3. Energy Types

Primary Energy Carriers	Final Energy Carriers
Coal	Coal
Oil products	Oil products
Natural gas	Methanol
Nuclear energy	Natural gas
Hydropower	Hydrogen
Biomass commercial	Electricity
Biomass noncommercial	District heat
Solar energy	Biomass commercial
Other renewables (wind, geothermal, wastes)	Biomass noncommercial
Total	Total
	Solar thermal energy

The WES Model is comprised of six modules (Figure A1). The WEC-IIASA global energy scenarios data is stored in several worksheets in the **Scenario Generator**. This database includes not only energy use, but also key drivers and indicators such as population, GDP, and energy intensities. The sheet also contains graphs of these variables to facilitate the comparison of scenarios and to aid in choosing a scenario for subsequent model runs.

The Scenario Generator allows the user to select a scenario from the input database and to modify that scenario by specifying alternative rates of change in the energy intensities for primary and final energy use, and by calibrating the scenario to base year 2000 energy use or to an IEO 2002 forecast.

Champagne Model Outputs for Canada and the United States must be stored in the North American/Conversion Module spreadsheets by the user. A Base Case, plus up to three alternative cases can be handled at one time. The North American/Conversion Module calibrates the modified global scenario to a Champagne Case, and converts an IEO forecast from quads to Gtoe for calibrating an IIASA/WEC scenario.

A modified and calibrated scenario is passed from the Scenario Generator to the Resource Accounting Module. Resource accounting is done twice. On the first iteration the calibrated scenario numbers are used to estimate resource depletion and initial requirements for unconventional resources, by region. The initial estimates of resource depletion by region are used to produce an initial petroleum price forecast. These are passed to the Oil Market Model where they are used to calibrate regional oil supply and demand curves, by year.

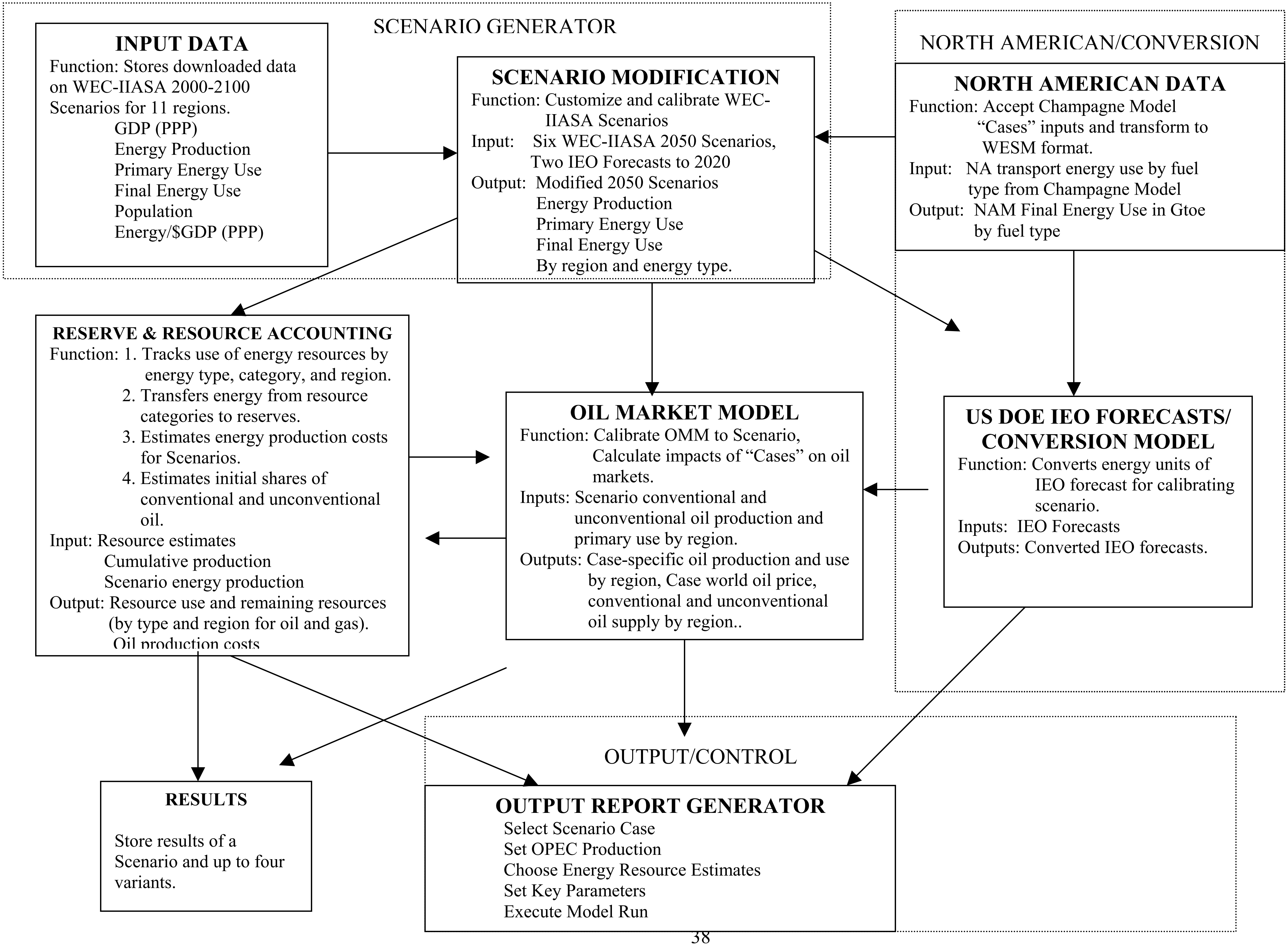
Oil primary energy use (Scenario Module) and production and price (Resource Accounting) from a calibrated Scenario-Case are passed to the Oil Market Model. The Oil Market Model then solves for a new oil market equilibrium by adjusting each year's world oil price until regional supply and demand of both conventional and unconventional oil equilibrate at a single world oil price. The model solves demand for all eleven regions and supply for ten regions. Production from the Middle East and Northern Africa region, currently used to represent OPEC, is exogenous. This allows the user to specify a particular pattern of behavior by OPEC, such as the simulation of a supply shock.

The results of the Oil Market Model equilibration are then passed to the Reserve & Resource Accounting Model, where the effects on rates of oil resource depletion are calculated.

Finally, results from the Conversion/Cost, Oil Market, and Reserve & Resource Accounting Models are collected in the **Output Report Generator**. In addition to collecting results from Scenario-Case runs, the Output Report Generator also controls the execution of sequential runs on Cases of a Scenario. Key assumptions are also assembled here to facilitate constructing and documenting model runs. The workbook also contains printable tables and graphs illustrating results.

WORLD ENERGY SCENARIOS MODEL STRUCTURE

July 23, 2002



SCENARIO GENERATOR

INPUT DATA

Function: Stores downloaded data on WEC-IIASA 2000-2100 Scenarios for 11 regions.
GDP (PPP)
Energy Production
Primary Energy Use
Final Energy Use
Population
Energy/$GDP (PPP)

SCENARIO MODIFICATION

Function: Customize and calibrate WEC-IIASA Scenarios
Input: Six WEC-IIASA 2050 Scenarios, Two IEO Forecasts to 2020
Output: Modified 2050 Scenarios
Energy Production
Primary Energy Use
Final Energy Use
By region and energy type.

NORTH AMERICAN/CONVERSION

NORTH AMERICAN DATA

Function: Accept Champagne Model "Cases" inputs and transform to WESM format.
Input: NA transport energy use by fuel type from Champagne Model
Output: NAM Final Energy Use in Gtoe by fuel type

RESERVE & RESOURCE ACCOUNTING

Function: 1. Tracks use of energy resources by energy type, category, and region.
2. Transfers energy from resource categories to reserves.
3. Estimates energy production costs for Scenarios.
4. Estimates initial shares of conventional and unconventional oil.
Input: Resource estimates
Cumulative production
Scenario energy production
Output: Resource use and remaining resources (by type and region for oil and gas).
Oil production costs

OIL MARKET MODEL

Function: Calibrate OMM to Scenario, Calculate impacts of "Cases" on oil markets.
Inputs: Scenario conventional and unconventional oil production and primary use by region.
Outputs: Case-specific oil production and use by region, Case world oil price, conventional and unconventional oil supply by region..

US DOE IEO FORECASTS/ CONVERSION MODEL

Function: Converts energy units of IEO forecast for calibrating scenario.
Inputs: IEO Forecasts
Outputs: Converted IEO forecasts.

OUTPUT/CONTROL

RESULTS

Store results of a Scenario and up to four variants.

OUTPUT REPORT GENERATOR

Select Scenario Case
Set OPEC Production
Choose Energy Resource Estimates
Set Key Parameters
Execute Model Run

A1.4 IMPLEMENTATION

The model has been implemented as a set of six, linked Excel™ Workbooks.

A run of the model requires (1) creating a scenario with the Scenario Generator, (2) inserting Champagne Model outputs in the North American/Conversion spreadsheet, and (3) entering key assumptions, executing a model run and printing output from the Output Report Generator.

A2. SCENARIO GENERATOR

The scenario generator contains the essential data from the six IIASA/WEC (Naki□enovi□, Grηbler and McDonald, 1999) Scenarios, and permits modification of these scenarios to create an initial WESM Scenario. The six IIASA/WEC Scenarios were driven by assumptions about population and economic growth, choices among primary energy sources, and the rate of technical efficiency improvement. The present version of the scenario generator allows for changes to the rate of technical efficiency improvement.

All six IIASA/WEC Scenarios assume major improvements in energy efficiency, as measured by energy use per dollar of GDP.[4] In the C Scenarios, energy use per dollar declines by a factor of five over the next century (Figure A2). By 2050, energy use per dollar is more than halved in the C Scenarios, and reduced by about 60 percent in the B and A Scenarios. While declining energy use per dollar of GDP has been a relatively consistent trend during the latter half of the 20th Century, it has not always been the case. It may be reasonable to examine future scenarios with less dramatic reductions in energy intensity.

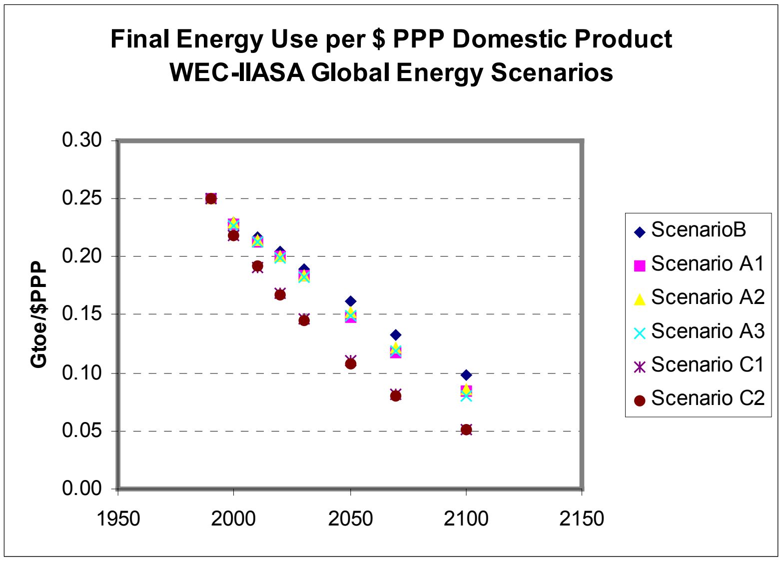


Figure A2.

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[4] The WEC-IIASA Scenarios provide GDP measured either in US dollars or adjusted for regional purchasing power parity (PPP). The WESM default is to use PPP-adjusted GDP.

From the patterns in Figure A1, it is evident that energy intensities decline approximately exponentially in all IIASA/WEC Scenarios. The average rates of decline in final energy use range from –0.7%/yr in the B Scenario to –1.3%/yr in the C Scenarios. Primary energy intensity declines even more rapidly, reflecting gains in the efficiencies of energy conversion technologies (Figure A3).

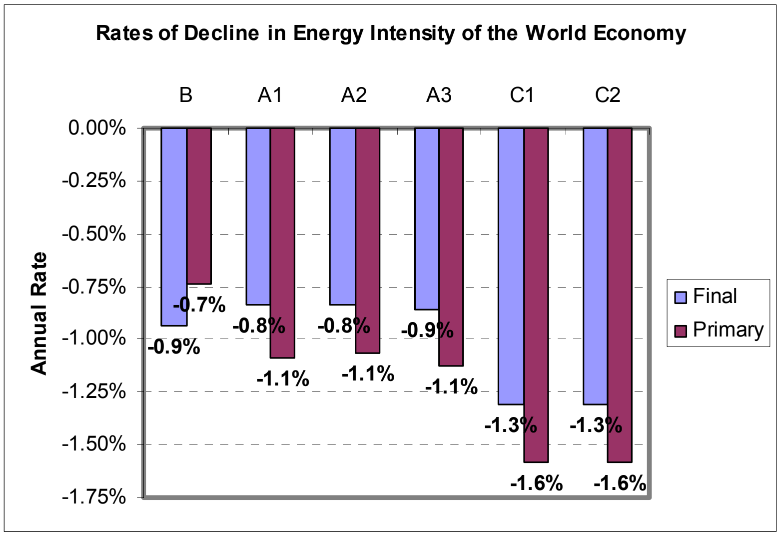


Figure A3.

The Scenario Generation spreadsheet allows the user to specify a new rate of change in energy intensity, in order to modify or override the rate implied by a WEC-IIASA Scenario. The rate of change in energy intensity may be increased or decreased by multiplying by the user-specified factor, r.

$$\left(\frac{E}{GDP}\right)_t^{NEW} = \left(\frac{E}{GDP}\right)_t (1+r)^t$$

Equation 1

For example, the rate of change in the energy intensity of final energy use in Scenario B is –0.9%/yr, which implies a ratio of 0.991 between succeeding years. By choosing r = 0.0091, the decrease in final energy intensity in the B Scenario would be effectively nullified (0.991□1.0091 = 1.00002). Final energy intensity would remain essentially constant. The Scenario generator allows different rate adjustment factors for final and primary energy intensity, but does not presently allow different factors for different fuel types.

Scenarios may be calibrated either to base year 2000 data or to one of three International Energy Outlook 2002 forecasts to 2020: (1) Reference Case, (2) High Economic Growth, and (3) Low Economic Growth. Calibration to base year 2000 simply factors the scenario projections up or down so that they pass through year 2000 actual energy supply and demand by region and fuel type. Calibration to an IEO 2002 forecast replaces the IIASA/WEC scenario energy production and final energy use with the IEO forecast through 2020. Energy use is not specified by the IEO forecast. It is factored up or down in proportion to the forecast's energy use. This procedure leaves a discontinuity between years 2020 and 2021. A weighted average splining method is used to smooth the transition from the IEO 2020 forecast back to the uncalibrated scenario.

A3. RESOURCE ACCOUNTING

The Resource Accounting Module tracks stocks (reserves and resources) and flows (production and transfers) by region and energy type, by year from 1996 to 2050. Beginning with initial estimates of world energy resources by energy type and resource category, this module performs the critical function of accounting for the use of oil and natural gas resources over time. It also predicts long-term trends in the costs of oil production as a function of the percent of ultimate resources that have already been produced. All the analyses are carried out at the regional level.

The accounting begins with an initial inventory of oil and gas resources by eight categories, following Rogner (1997). The eight categories describe the world's oil and gas resources according to the likely cost of development and the degree of certainty about their existence and extent. To this, a ninth category, resources already produced, is added. The inventory is updated to 2000 based on production of crude oil and natural gas liquids. Production of oil by region, as specified in a Scenario, is subtracted from proved reserves (Category I). Two types of proved reserves are tracked, conventional and unconventional. Other categories of oil are transferred to proved reserves over time depending on the rate of production and user-specified, exogenous assumptions. Thus, there are continuous flows of oil out of proved reserves to Production, and into proved reserves from other resource categories. The definitions of reserve categories are essential to understanding the logic of these resource flows.

A3.1 RESOURCE CATEGORIES

Accounting for resources begins with base year inventories of fossil energy resources. Three sources have been used for estimates of oil, gas and coal energy by resource category: (1) Rogner, 1997, (2) U.S.G.S., 2000, and (3) Laherrere, 2001. Cumulative production to date based on U.S.G.S. (2000) is used for all three sets of resource estimates.

Rogner (1997) distinguishes eight resource categories for oil and gas occurrences and ten for coal (Table A4). Only six categories are accounted for. Additional occurrences (categories VII and VIII) are comprised of very low-grade resources and resources unrecoverable (left in situ) after enhanced recovery. They assumed not to be used before 2050. Definitions of the six categories are as follows:

> Category I: Known, measured reserves that are either known or believed to be economically recoverable. This includes both proved and probably reserves.

Table A4. Estimates of Oil Occurrences, 1995, in Gtoe[a]

		World Petroleum Resources								
		Conventional oil				Unconventional oil reserves and resources				
						Aggregate of shale, bitumen, and heavy oils				
Region	Cumulative Production 1/1/1996	Proved Recoverable Reserves I	Estimated Additional Reserves II	Additional Speculative Resources III	Enhanced Recovery IV	Recoverable Reserves V	Resources VI	Additional Occurrences VII	VIII	Total
NAM	**27.5**	8.5	8.6	6.7	15.9	7.6	98.8	172.8	287.4	606.3
WEU	**3.8**	5.6	2.1	3.6	5.1	1.3	7.6	13.3	34.6	73.2
PAO	**0.6**	0.4	0.3	0.6	0.7	3.7	25.8	45.1	60.3	136.9
FSU	**16.7**	17.1	13.6	19.3	23.4	3.3	19.4	34.0	125.6	255.7
EEU	**0.8**	0.3	0.2	0.6	0.7	0	0.5	1.0	3.8	7.1
LAM	**12.7**	17.4	8.9	15.5	18.9	2.6	91.5	160.1	270.8	585.7
MEA	**32.0**	87.9	17.0	21.9	56.2	22.3	39.6	69.3	279.0	593.2
AFR	**3.3**	4.0	3.4	4.9	5.4	1.4	5.1	8.9	29.7	62.8
CPA	**3.5**	5.1	4.7	8.2	7.4	2.3	42.2	73.8	118.7	262.4
PAS	**3.1**	2.9	1.6	2.5	3.4	0.6	4.8	8.3	23.0	47.1
SAS	**0.7**	1.0	0.3	0.6	0.8	0.1	0.3	0.5	3.5	7.1
World[b]	**104.8**	150.2	60.7	84.4	137.9	45.2	335.6	587.1	1236.4	2637.5
World	86.4									

Check Cumulative Production for accuracy: Source USGS? GEPs says about 90 Gtoe produced by 1990, Rogner 109 by 1994

[a] Compiled from Tables 2 and 3

[b] Totals may not add up owing to rounding.

Category II: Undiscovered occurrences that are believed to exist and have a reasonable probability of being discovered and of being economically developable. Presumably, exploration and development efforts will replenish Category 1 reserves with Category 2 resources. Roughly intended to correspond to Masters', et al. (1994) "mode or 50 percent probability of being discovered", or to the WEC definition of "estimated additional reserves".

Category III: More speculative resources, roughly corresponding to the difference between Masters', et al. (1994) 50 percent and 5 percent probability estimates of undiscovered oil and gas. Using this definition, the most likely estimate of the size of these reserves would be zero.

By definition, Category I-III resources are believed to be developable with the application of existing recovery technology. What distinguishes them is the certainty with which they are known or believed to exist.

Category IV reflects the potential for technological advances to enhance oil recovery and thereby increase the fraction of in situ oil recoverable from existing and future fields. According to Rogner's definition this category does not represent undiscovered oil, but technological advances permitting greater production from Categories I-III. In the past, 34 percent of oil and 70 percent of in situ gas has been recoverable. Rogner (1997) assumes that for Categories I-III, 40 percent of oil and 80 percent of gas will be recoverable. In the United States, the average recovery rate for fields in the lower 48 states increased from 1967 to 1979 at an average annual rate of 0.2 percent (Porter, 1995), and further increases are likely in the future. However, we use the USGS 2000 category of "reserve growth" as Category IV oil. There is considerable controversy about this estimate, as explained in Part I of the main body of the report. The USGS apparently intends it to represent the effects of both technology and initial underestimation of field sizes.

Categories V-VIII represent unconventional sources of oil and gas. Unconventional oil resources include extra heavy oils, oil and tar sands, deep-sea oils, bitumen, and shale oil. Unconventional natural gas includes gas in Devonian shales, tight sandstone formations, geopressured aquifers, coal bed methane, and methane hydrates. In some cases, synthetic crude oils are already being produced from these sources (e.g., Canadian Athabasca Oil Sands). In others, such as the 85 percent of oil shales that contain less than 0.08 percent oil by weight or deep sea methane hydrates, serious questions exist about whether these resources could ever be produced economically.

Category V comprises the identified reserves of unconventional oil and gas. It is the sum of WEC (1992) estimated shale reserves, BGR (1995) tar sands reserves and Meyers, et al. (1988) estimated heavy oil reserves. These are the reserves that can be produced economically at current market prices. Of course, their production costs are higher than those of conventional oil, so their economics is vulnerable to price fluctuations caused by the manipulation of world oil supply.

Rogner allocated all remaining occurrences between categories VI, VII and VIII according to a 20:35:45 ratio. In addition, all the oil remaining in the ground after conventional *and enhanced* recovery is allocated to Category VIII. Categories VII and VIII have been excluded from production by 2050 in the November 2001 version of the model.

A3.2 RESOURCE STOCKS AND FLOWS

Category I, Proved Reserves

Regional Proved Reserves (I) and Unconventional Recoverable Reserves (V) are the sole sources for regional oil production. All other categories of conventional oil resources may flow into proved reserves, but production can be taken only from proved reserves. Similarly, unconventional resources (VI) may flow into unconventional recoverable reserves (V), but production may come out only from unconventional recoverable reserves. In the equations below, regional subscripts have been omitted for simplicity, although all calculations are carried out at the regional level.

The equation for the stock of proved reserves at the beginning of year t, X_{Pt} , consists of last year's proved reserves X_{Pt-1} (at the beginning of the year), minus last year's production, V_{Pt-1} , plus reserve expansion at the rate of □100 percent per year, plus the inflow from estimated additional reserves, V_{At-1} , plus the inflow from speculative reserves, V_{St-1} . The rate of reserve expansion is a user-specified parameter. Once the stocks of category IV (EOR/Reserve Growth) have been exhausted, reserve expansion ceases.

$$X_{Pt} = X_{Pt-1} - V_{Pt-1} + \delta X_{P1995} + V_{At-1} + V_{St-1}$$

Equation 2

The flow from proved reserves, V_{Pt} , is equal to the quantity of production required by the scenario, Q_t , provided that the reserve to production ratio, (R/P) = (X_{Pt} / Q_t) . □ , a target R/P ratio. Otherwise, only a fraction of production is taken from proved reserves. The fraction is a logistic function of the R/P ratio.

$$V_{Pt} = Q_t \qquad if \qquad \frac{X_{Pt}}{Q_t} \geq \rho$$

$$Otherwise,$$

$$V_{Pt} = Q_t \left[1 + e^{\beta_o + \beta_1 (\rho - (X_{Pt}/Q_t))} \right]^{-1}$$

Equation 3

The ratio of the two coefficients, $_o$ and $_1$ determines the R/P ratio at which 50 percent of production will be satisfied from current reserves ($_o$/$_1$). The rate at which production will decline as the R/P ratio diminishes is determined by $_1$. This formulation prevents the stock of proved reserves from becoming negative, but also allows for a more realistic gradual decline in production as reserves are depleted. The model user must specify the target R/P ratio, the R/P value at which 50 percent of production will be taken from proved reserves and the rate parameter. $_{1}$.

The transfer from additional reserves to proved reserves is taken to be a fraction of the previous year's production $V_{At} = \square Q_{At-1}$, where $\square \leq 1$. In general, □ will be quite close to 1, say 0.9, since estimated additional reserves should be the most likely source from which to replenish proved reserves. However, if the call on additional reserves exceeds the stock of additional reserves, then $V_{At} = pX_{At-1,}$ where p is a smaller proportion, generally $p \leq 0.5$. The stock of additional reserves, X_{At} , depends on the outflow and on reserve expansion.

$$X_{At} = X_{At-1} - V_{At-1} + \delta X_{A1996}$$

Equation 4

Category III, Additional Speculative Resources

Rogner (1997) defines Category III resources as the difference between Masters' et al. (1994) 50 percent probability estimate of recoverable conventional oil resources and their 5 percent estimate. Thus, according to Masters et al., the most probable amount of oil that will be found in this category is zero. Nonetheless, one may wish to explore the implications of more optimistic views, in which some fraction of this oil will be discovered and prove to be economically recoverable.

The user specifies three parameters that determine: (1) the quantity, X*, of speculative resources that will ultimately be developed, as a fraction of the total available, (2) the quantity of those resources already converted to proved reserves by 2000, and (3) the year, τ, in which half of the available Category III oil will have been discovered and transformed to Category I oil (proved reserves).

The following simple model is used to represent the discovery of speculative resources (i.e., their conversion to proved reserves). The derivation is similar to Reynolds' (2002, ch. 1) derivation of the Hubbert model. Let X* be the ultimately recoverable quantity of speculative resources for region r (the subscripts r and s are omitted for simplicity). Let X_t be the cumulative quantity discovered at time t. It is assumed that the rate of discovery, dX_t/dt, is simultaneously proportional to: (1) the state of knowledge about the resource, and (2) the amount of the resource that remains to be discovered (X^*-X_t). The state of knowledge is assumed to be proportional to the amount of the resource already discovered (i.e., αX_t, where α is an empirical learning rate). That is, as more of the resource is discovered, more is learned about the location and condition of the remaining resource. This formulation leads to a non-linear differential equation.

$$\frac{dX_t}{dt} = \alpha X_t\left(X^* - X_t\right) = \alpha X^*\left(1 - \frac{X_t}{X^*}\right)X_t$$

Equation 5

Its solution is the following logistic equation, in which X_o is a constant to be determined by initial conditions.

$$X_t = \frac{X_o X^*}{X_o + (X^* - X_o)e^{-\alpha t}}$$

Equation 6

The initial conditions can be specified in terms of the cumulative quantity of speculative resources, X_o , that have been converted to proved reserves in the base year (2000). In general, this will be a small number. The amount, X_o , is added to proved reserves for 2000 so that the quantity previously converted is not lost.

The S-shape of the logistic function implies that the conversion of speculative resources to proved reserves will follow a Hubbert curve. The rate of conversion will reach a maximum when $X = X^*/2$, i.e., when half of the speculative resources have been converted. The model user must specify this halfway year, τ , and then the rate parameter α can be obtained by solving equation (6) for α, with $X_t = X^*/2$.

$$\alpha = -\frac{1}{\tau}\ln\left(\frac{X_o}{X^* - X_o}\right)$$

Equation 7

The flow of speculative resources is their discovery and thereby their conversion into proved reserves. The logistics curve describes the cumulative discovery of speculative resources as a function of time. A year's flow is thus the difference between cumulative discovery at the end of the year and at the beginning. The pattern of annual discovery (conversion to proved reserves) will exhibit the classic Hubbertian bell shape, though it will be somewhat thicker on the declining side due to reserve expansion.

$$V_{st} = X_{st} - X_{st-1}$$

Equation 8

The stock of speculative reserves also allows for reserve expansion due to enhanced recovery.

$$X_{St} = X_{St-1} + \gamma\delta X_{S1996} - V_{St-1}$$

Equation 9

This equation allows reserve expansion only for the fraction of speculative reserves believed to exist ().

Category IV, Enhanced Recovery

Category IV resources represent the potential for technological advances, and perhaps higher oil prices, to permit the economic recovery of a greater percentage of in situ oil. Historically, only about 35 percent to 40 percent of the oil in situ could be economically recovered, but recovery rates have been improving over time. Porter (1995, pp. 36-37), for example, cites an expansion rate of 0.2%/year for reserves in the lower 48 between 1966 and 1979. There is substantial controversy about the amount that EOR will contribute to the world's proved reserves over the next 50 years.

Since "flows" from enhanced recovery, as seen in the equations above, are calculated as a percentage of the total base year resource quantity, it is only necessary to keep track of the stock, X_{Et} .

$$X_{Et} = X_{Et-1} - \delta(X_{P1996} + X_{A1996} + \gamma X_{S1996})$$

Equation 10

Categories V and VI, Unconventional Recoverable Reserves and Resources

Recoverable reserves of unconventional resources are known and can be produced at or near current energy prices. In this sense they are more like proved reserves than like other resource categories. A key issue is how to determine when unconventional oil will penetrate the world oil market and what its share will be. The Resource Accounting and Oil Market Modules handle this in two steps. First, unconventional recoverable reserves are treated as a regional backstop for proved reserves. They are produced whenever the call on production from a region, P_t , cannot be satisfied from proved reserves (Category I).

$$V_{Ut} = P_t - V_{Pt}$$

Equation 11

V_{Ut} will be greater than zero when a region's R/P ratio falls below the user-specified critical level. Second, the initial regional "backstop" estimates of unconventional oil production are passed to the Oil Market Module. There, supply curves are calibrated that pass through the backstop production level at a price estimated by unconventional oil regional depletion/cost curves. A market equilibration process then determines the second-round estimates of conventional and unconventional oil supply, by region. If the cost of producing unconventional oil from a given region is high relative to the cost of conventional oil from other regions, the market equilibration will shift production away from unconventional and towards conventional oil. The reserve could occur if a region's conventional oil resources became severely depleted.

The second-round estimate of unconventional oil production is passed back to the Resource Accounting model, where a second, final accounting of resource depletion is carried out. If the quantity of unconventional oil required in the second-round exceeds available reserves of unconventional oil, the deficit is supplied by a generic backstop energy source to prevent stocks from going negative.

The stock of unconventional recoverable reserves receives an inflow, V_R , from unconventional resources (Category VI) as these resources are discovered and as technology advances to permit their economical recovery.

$$X_{Ut} = X_{Ut-1} - V_{Ut-1} + V_{Rt-1}$$

Equation 12

The flow from unconventional resources to unconventional reserves, V_{Rt} , like the flow from speculative reserves to proved reserves, depends on user-specified parameters of a logistic discovery function. Flows and depletion are handled in the same way, as well.

$$V_{Rt} = X_{Ut} \frac{1}{\theta\sqrt{2\pi}} e^{-(t-t_\eta)/2\theta^2}$$

Equation 13

A3.3 DEPLETION-BASED PRODUCTION COST ESTIMATION

The Reserve and Resource Accounting Module produces an initial estimate of the long-run price of oil, based on estimated marginal costs of production by region. Marginal production costs are estimated as a function of the state of depletion of the region's ultimate resources (as opposed to reserves) of conventional oil.

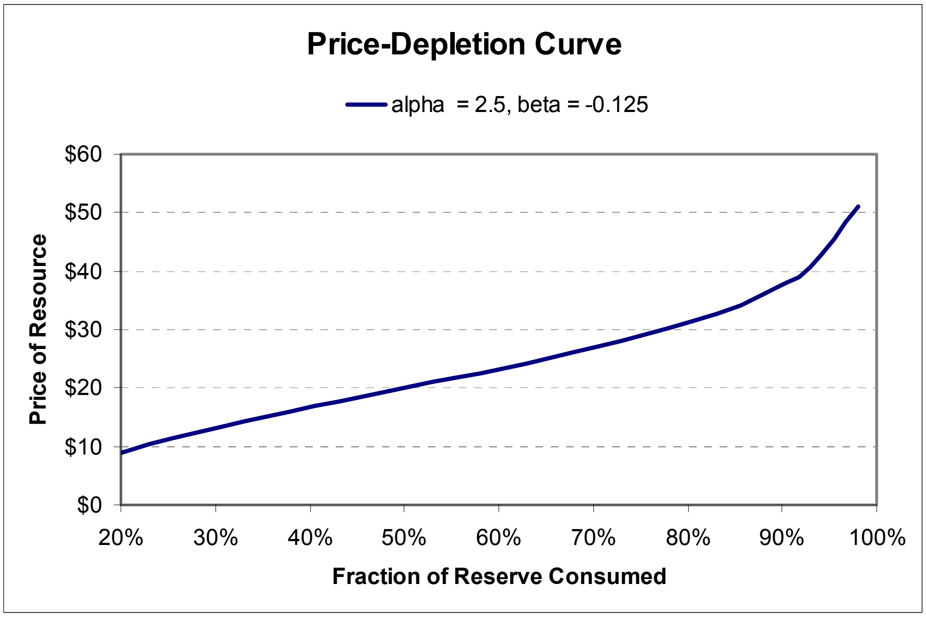
Following an approach outlined by Rogner (1997), production costs, C_{rt} , are assumed to rise as a logistic function of the state of depletion, $\square_{rt}$, of total resources. State of depletion is defined as the fraction of total resources that have been consumed at time t. Total resources are defined as the sum of cumulative production, proved reserves, estimated additional reserves, plus the fraction of additional speculative reserves assumed to exist, plus reserve expansion due to enhanced recovery over the period 1995 to 2050. The price rise with state of depletion depends on parameters defining the slope, , and intercept, $_r$, of the logistic curve. Intercepts are allowed to vary across regions in order to calibrate the depletion cost curves to historical production cost data.

$$P_{rt} = \left(\ln\left[\frac{1}{\phi_{rt}} - 1 \right] - \alpha_r \right) \Big/ \beta$$

Equation 14

An illustrative curve is shown in Figure A4.

Figure A4.



Because P_{rt} would otherwise approach infinity as the state of depletion approached 1.0, an upper bound is set on □$_{rt}$. This upper bound, in effect, defines a backstop price for liquid fuels from other energy sources. An initial estimate of the world marginal cost of oil is defined as the □th percentile of the depletion-based production costs across all oil-producing regions in year t. The percentile is a user-specified parameter. Each year's initial regional depletion prices are treated as samples from a normal distribution. The mean and standard deviation are computed, and the □th percentile price is calculated. This price is used by the Oil Market Module as an initial estimate of the market equilibrium oil price.

The depletion parameters α and β can be given a concrete interpretation that is useful for calibration of the equations. By substituting $\phi = 0.5$ in equation 2, the equation simplifies to $P = -\alpha/\beta$. Thus, the price at the midpoint of depletion is the negative of the ratio of the two parameters. By differentiating price with respect to ϕ , an expression relating the change in price to a change in percent depletion can be derived.

$$\frac{dP}{d\phi} = \frac{d}{d\phi}\left(\ln\left[\frac{1}{\phi_{rt}}-1\right]-\alpha_r\right)\Bigg/\beta = \frac{1}{\beta}\frac{1}{\left(\frac{1}{\phi}-1\right)}\frac{-1}{\phi^2} = \frac{-1}{\beta\phi(1-\phi)}$$

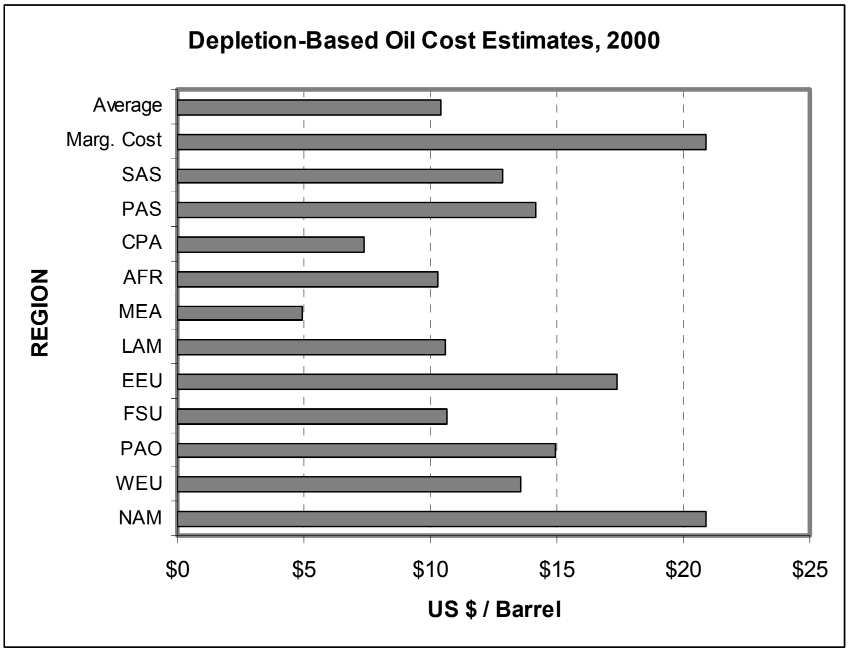
Equation 15

This expression shows that the slope of the depletion-price curve depends on the state of depletion, and that it will be at a minimum when $\phi = 0.5$. These two equations provide an expression for the median price and the slope at the median price. Note that the slope at the median price depends on β alone. If $\beta = -0.15$, then the slope at $\phi = 0.5$ is 26.67. This implies that a unit change in ϕ would produce a price change of $26.67 per barrel. But $0<\phi<1$, so that a change in ϕ of 1.0 is a very large change. In the vicinity of 0.5, a change in ϕ of 0.01, would change price by about \$0.27, or a change of 0.1 (a 10 percent increase in depletion) would increase price by about \$2.67 per barrel. Since the depletion price curve is nearly linear over a wide range near $\phi = 0.5$, the slope given by equation 3 is a useful indicator of the price sensitivity implied by any particular choice of β.

Having chosen a value for β, region-specific values for α can be chosen by making use of $P = -\alpha/\beta$. Again, suppose $\beta = -0.15$. Then $\alpha = 2$, implies a median price of \$13.33 per barrel, while $\alpha = 4$ implies a price of \$26.67 per barrel at 50 percent depletion. The parameter α is used as a general indicator of the quality (ease of discovery and development) of resources in a region, while β describes the sensitivity of price to state of depletion.

Production cost estimates can be obtained from a variety of sources. Production costs for the Middle East regions were based on U.S. DOE/EIA (1996). Cost estimates for other regions have been published in Porter (1995) and Stauffer (1994). Given the depletion-cost curve with parameters = 3.0 and = -1.5, cost estimate for each region as a function of its estimated 2000 depletion level are shown in Figure A5.

Figure A5.



To simplify calibration and for lack of more detailed information, the same slope value, $\beta = -0.15$, is used for all regions. This is quite similar to the price slope that can be inferred from data presented in Rogner (1997). Regions are then characterized as low cost, moderate or high cost, and assigned values of $\alpha = 2.0$ to 4.0. Inserting the actual year 2000 depletion status of each region into equation 2, and using the appropriate regional parameters produces the estimated year 2000 oil production costs shown in Table A5. These estimates are roughly comparable to country-specific production cost estimates provided by Stauffer (1994). It is intended only that the costs be generally similar, inasmuch as the data necessary to compute weighted average production costs for each region are not available.

Table A5. Conventional Oil, 2000

Slope Parameter Beta	Price Increase per 10% depletion at	50%
-0.15	Depleted =	**$2.67**

Region	Production	Reserves	R/P	Resources/P	In 2000 % Depleted	Intercept Parameter Alpha	Regional Midpoint Price	Price at /% Depleted
NAM	0.598	8.652	14.5	39.2	56.2%	3.0	$20.00	$21.80
WEU	0.376	5.658	15.0	27.7	34.5%	4.0	$26.67	$15.80
PAO	0.031	0.405	13.1	35.6	40.4%	3.5	$23.33	$13.52
FSU	0.414	17.539	42.3	119.5	27.1%	3.0	$20.00	$10.69
EEU	0.016	0.310	19.3	59.5	48.8%	3.5	$23.33	$23.21
LAM	0.575	17.752	30.9	71.0	27.0%	3.0	$20.00	$11.52
MEA	1.354	89.840	66.4	104.2	21.3%	2.0	$13.33	$2.90
AFR	0.236	4.064	17.2	49.1	26.6%	3.0	$20.00	$8.29
CPA	0.170	5.222	30.7	99.0	20.5%	3.0	$20.00	$15.71
PAS	0.178	2.948	16.6	37.2	36.5%	3.0	$20.00	$15.44
SAS	0.054	1.020	18.9	33.9	32.3%	3.5	$23.33	$16.21

Only the Middle East region is categorized as very low cost. This, combined with a low level of resource depletion implies a year 2000 production cost of about $3 per barrel. Regions in the moderate cost group include states of the Former Soviet Union, Latin American and Africa. Higher cost regions include North America, Western Europe and China. North America's high cost α parameter, together with its high depletion level of 56 percent combine to give it the highest production cost estimate, $22 per barrel. These cost estimates are highly uncertain and could benefit from a thorough analysis of more comprehensive regional production cost data.

Finally, it is reasonable to expect that production costs at any level of depletion will decline over time as exploration and extraction technology improve. A technological change parameter (-1 □ < □) may therefore be specified in terms of a percent change in costs per year. This parameter is applied to the cost curve intercept term, α, to shift the curve downward over time.

$$\alpha_t = (1+\theta)\alpha_{t-1}$$

Equation 16

A4. OIL MARKET MODULE

The Oil Market Module is a simplified representation of the world oil market. In it, Regional oil supply and demand equations are calibrated to precisely fit the primary energy oil use and oil production of a Scenario produced by the Scenario Generator Module and the initial depletion costs associated with that scenario produced by the Resource Accounting Module. Supply curves are calibrated for both conventional and unconventional oil, by region. There are twenty supply curves and eleven demand curves for each year because Middle Easter oil producers' (MEA) oil supply is specified exogenously. While total MEA oil supply is given, it is divided between conventional and unconventional oil according to the same methods used for all other regions.

Production of oil by MEA is an exogenous, reflecting the assumption that OPEC producers are not price takers, but select output levels in order to influence market prices. A Case may therefore include alternative assumptions about supply available from these producers. In particular, price shocks could be created by suddenly reducing OPEC production.

The calibration of supply and demand equations also requires user-specified assumptions about the price elasticities of oil supply and demand, and the rates of adjustment of supply and demand to price changes. Given these assumptions, the coefficients of linear supply and demand equations are calculated to precisely fit the Scenario under consideration. Both supply and demand equations are assumed to have the linear lagged adjustment form.

$$Q_{rt} = A_{rt} + B_{rt}P_t + \Lambda Q_{rt-1}$$

Equation 17

$$q_{rt} = a_{rt} + b_{rt}P_t + \lambda Q_{rt-1}$$

Equation 18

The lagged adjustment coefficients, □ and □, control the rates at which markets respond to changes in prices and quantities, and are exogenously specified by the model user. The user must also specify the elasticities of supply and demand. At present, these elasticities may be different for North America and the rest of the world (ROW), although a future version could allow different elasticities for each region. Both the lagged adjustment coefficients and the elasticities are assumed to remain constant over time (again, this could be relaxed in a later version of the model).

Regional price slopes (B_{rt} and b_{rt}) are calculated using the assumed price elasticities, ($_r$ and $_r$) regional production (Q_{rt}) and primary energy use (q_{rt}) volumes, and world oil price (P_t).

$$B_{rt} = \beta_r \frac{Q_{rt}}{P_t}$$

Equation 19

$$b_{rt} = \eta_r \frac{q_{rt}}{P_t}$$

Equation 20

Given price slopes for the supply and demand equations, intercepts can be calculated using the relevant prices and quantities.

$$A_{rt} = Q_{rt} - B_{rt}P_t - \Lambda Q_{rt-1}$$

Equation 21

$$a_{rt} = q_{rt} - b_{rt}P_t - \lambda q_{rt-1}$$

Equation 22

These sets of coefficients specify individual oil supply and demand equations for each region and year that precisely match the modified WEC-IIASA scenario at the world oil price projected for each year, given the regional elasticities and lagged adjustment rates specified. No supply coefficients are estimated for OPEC (represented at present by the Middle-East Region), since their supply decisions are assumed to be exogenous. This is consistent with a world oil market in which the OPEC cartel acts as a monopolistic dominant producer, while the rest of the world producers are competitive price takers.

Changes in world oil supply or demand brought about by a Champagne Model CASE forecast can be represented as shifts in the North American supply and demand equations. In principle, these shifts could affect the slopes or intercepts of the curves. At present, only shifts in the NAM demand curve are permitted, and these are represented as shifts in the intercept of the demand curve, holding its slope constant.

Starting from Oil Demand Equation 1, above, the shifted demand, q'_{rt+1}, and its shifted intercept, a'_{rt+1}, produce the following shifted demand equation.

$$q'_{rt+1} = a'_{rt+1} + b_{rt+1}P_{t+1} + \lambda q'_{rt}$$

Equation 23

The new intercepts, a'_{rt+1} , are derived by subtracting oil demand equation 4 from equation 1.

$$a'_{rt+1} = a_{rt+1} - (q_{rt+1} - q'_{rt+1}) + \lambda(q_{rt} - q'_{rt})$$

Equation 24

A new equilibrium is found by solving the system of world oil supply-demand equations using the new intercepts for North America. Because all supply and demand equations are linear, and dependent variables depend only on current price and lagged dependent variables, the system of supply and demand equations can be solved, recursively, in closed forum. This produces a single world price that equates the sum of oil supplies across regions to the sum of demands.

$$\sum_{r \neq OPEC} \left[A_{rt} + B_{rt} P_t + \Lambda Q_{rt-1} \right] + Q_{OPEC} = \sum_{r=1}^{11} \left[a_{rt} + b_{rt} P_t + \lambda q_{rt-1} \right]$$

Equation 25

The resulting forecast of supplies, demands and world oil prices constitutes a SCENARIO-CASE. The initial version of the model does not equilibrate markets other than the oil market, and does not take account of feedbacks between world energy markets and economic growth. Future versions may do so.

A5. NORTH AMERICAN /CONVERSION MODULE

The North American/Conversion Module accepts Champagne Model Outputs for Canada and the United States (Mexico to be added), summarizes and reformats the outputs for use in the Energy Conversion/Cost Module. A Base Case and up to six alternative cases can be accepted at one time. At present, this module is contained within the same spreadsheet as the Conversion/Cost Module, entitled ConversionCost.xls.

A5.1 RECONCILING WORLD ENERGY SCENARIO TO CHAMPAGNE MODEL RESULTS

The Champagne Models for Canada and the U.S. (and eventually Mexico) cover transportation energy use only. While this will represent the majority of petroleum use in North America, it will not represent the entire amount of any final energy carrier. On the other hand, the World Energy Scenarios do not break out final energy use by transportation, or any other sector. This means that is it not possible to simply replace WES transportation energy estimates with Champagne results, nor to factor the WES numbers up or down by multiplying by fuel-specific factors. A different approach based on the relationship of the two forecasts has been adopted.

The logic of the reconciliation approach is based on which projection of final energy use is greater in 2000 and in 2050. Normally, one would expect the WES estimate of any particular type of final energy carrier to exceed that of the Champagne Model, since the Champagne Model covers the transportation sector only. If the Champagne model forecast for a particular final energy carrier in 2000 exceeds the WES forecast, then the two are in conflict. The same applies for the year 2050. The logic of the reconciliation approach is to adopt the Champagne Model forecast when it exceeds the WES forecast for a final energy carrier. When the WES forecast is greater, it is assumed that the difference will remain constant for all Champagne Model Cases.

The reconciliation process calculates a matrix of deltas, or differences between a modified scenario and a Base Case Champagne Model run. The deltas are then added to alternative Champagne Cases to produce a complete picture of energy use by the North American economy. A key feature of this method is that the differences in energy use between Champagne Cases are preserved in the final WES Model Scenario-Cases. The detailed logic follows.

Let $E_{N,f,t}$ represent WES North American use of final energy carrier f, in year t. Let $e_{N,f,t}$ represent the Champagne Model's estimate of transportation energy use.

1. If $E_{N,f,2000} > e_{N,f,2000}$, then,
    a. If $E_{N,f,2050}\ .\ e_{N,f,2050}$, let the initial difference $\square_{f,2000}$ decrease linearly to zero by 2050. In effect, it is assumed that the other sectors' use of oil is decreasing from $\square_{f,2000}$ to zero by 2050.
    b. If $E_{N,f,2050} > e_{N,f,2050}$, (the WES forecast is always greater) let $\square_{f,t} = E_{N,f,t} - e_{N,f,t}$.
2. If $E_{N,f,2000} = e_{N,f,2000}$, then,
    a. If $E_{N,f,2050}\ .\ e_{N,f,2050}$, then use $e_{N,f,t}$ for all t.
    b. If $E_{N,f,2050} > e_{N,f,2050}$, then calculate $\square_{f,t} = E_{N,f,t} - e_{N,f,t}$.
3. If $E_{N,f,2000} < e_{N,f,2000}$, then,
    a. If $E_{N,f,2050}\ .\ e_{N,f,2050}$, then use $e_{N,f,t}$ for all t.
    b. If $E_{N,f,2050} > e_{N,f,2050}$, then calculate $._{N,f,t} = (e_{N,f,2000} / E_{N,f,2000})\, E_{N,f,t}$, and let $\square_{f,t} = ._{N,f,t} - e_{N,f,t}$.

A5.2 INTERNATIONAL ENERGY OUTLOOK - WESM CALIBRATION

There are three basic steps in the calibration of the IIASA data to the International Energy Outlook data:

1. Matching regions and fuel types
2. Inferring Final Energy and Production data from the Primary Energy
3. Splining the IEO forecasts to the IIASA data.

A5.2.1 Matching Regions and Energy Types

In order to spline the IEO data to the IIASA data we first modified the regions and fuel types used in the IEO data to match the regions and fuel types defined in the IIASA data.

Hydroelectric energy and renewable energy are combined in a single consumption table in the IEO data. The IIASA data provides separate forecasts of primary energy for hydroelectric energy, commercial biomass, non-commercial biomass, solar and other energy. Using IIASA's shares of different energy types we subdivided the IEO data into separate forecasts for hydroelectric energy, commercial biomass, non-commercial biomass, solar and other. All of the other IEO energy consumption tables match the categories used in the IIASA data.

The regions defined in the IEO data do not match those used in the IIASA data. First, we attempted to summarize country level data from the IEO in order to match the IIASA regions. Since, the IEO did not provide country level data for all regions, this was not always possible. For example, IEO combines all countries of developing Asia into a single region whereas this region is subdivided into Centrally Planned Asia, South Asia and Other Pacific Asia in the IIASA data. Using IIASA's shares of for these regions we subdivided the IEO data into separate forecasts for Centrally Planned Asia, South Asia and Other Pacific Asia.

A5.2.2 Inferring Final Energy and Production data from Primary Energy

The IEO Final Energy is estimated as follows:

1. For oil, natural gas and coal the IEO Final Energy is assumed to be equal to Primary Energy (i.e. EIA's consumption tables).
2. Electricity final energy is assumed to be the sum of hydroelectric + nuclear primary energy
3. The shares of IIASA Final Energy for Methanol, Hydrogen, and Dist Heat (WEM-EIA sheet) are used to convert the IEO "other" primary energy to Final Energy Categories of Methanol, Hydrogen, and Dist Heat(WEM-EIA sheet).

The IEO provides production estimates for oil for the reference case only. The oil production for the high and low growth cases were estimated using the reference case production and the high and low growth oil consumption tables.

Coal and natural gas production were estimated using the IEO consumption data and IIASA's production shares. Production for all other fuel types (nuclear, hydroelectric energy, commercial biomass, non-commercial biomass, solar and other energy) is assumed to be equal to consumption.

A5.2.3 Splined Forecasts

At this stage, data are available for 2000, 2010, 2020, 2030 and 2050 only. Intervening years must be interpolated. The International Energy Outlook forecasts are used for years 2000-2020. Beyond 2020, the data are from a modified IIASA/WEC Scenario. This may result in a discontinuity between 2020 and 2030. Splining is used to make a smooth transition from the IEO to IIASA/WEC scenarios. The splining method used recognizes that the IEO forecast may have a different trend from the IIASA/WEC forecast. The spline should therefore attempt to reconcile, 1) continuing the IEO trend and, 2) moving toward the IIASA/WEC forecast.

An IEO trend estimate for 2030 is created by linear extrapolation of the IOE 2010 to 2020 trend. A weighted average of this trend forecast and the 2030 IIASA/WEC forecast becomes the splined forecast. The energy for 2030 is calculated as follows:

$$\text{Energy}_{Y2030} = \text{alpha}((\text{IEO}_{Y2020} - \text{IEO}_{Y2020}) + \text{IEO}_{Y2020}) + (1\text{-alpha})^{*}\ \text{IIASA}_{Y2030}$$

For 2050 there is no reasonable basis for projecting the IEO forecast. Instead, the splined forecast is a weighted average of the IIASA/WEC 2050 Scenario and a linear extrapolation from the 2030 splined forecast, based on the 2030 to 2050 trend of the IIASA/WEC Scenario. The formula for the 2050 splined forecast is as follows:

$$\text{Energy}_{Y2050} = \text{alpha}((\text{IIASA}_{Y2050} - \text{IIASA}_{Y2030}) + \text{Energy}_{Y2030}) + (1\text{-alpha})^{*}\ \text{IIASA}_{Y2050}$$

The default value for alpha is 0.7, but it can be set to any value the model user chooses.

A6. OUTPUT/CONTROL MODULE

The Output/Control Module is the control center for executing a model run. One spreadsheet contains all the key parameter assumptions that must be made for a model run. From this same spreadsheet, the user initiates iterative runs of the up to four Cases of a Scenario. The Output/Control Module also sends tables and figures summarizing the results of the Scenario-Cases to the Results Module.

A7. PROCEDURE FOR EXECUTING A MODEL RUN

Executing a model run requires five steps (Figure A3):

I. From the Scenario Generator, create a scenario

  1. Select a representative WEC-IIASA Scenario.
  2. Customize the Scenario, by adjusting energy intensity (and other parameters).
  3. Calibrate the Scenario to either the base year (2000) or to an IEO 2002 projection.
  4. Copy champagne model runs for Canada and United States

II. From the Output Report Generator, execute a model run

  1. Select a Scenario.
  2. Select the resource data to be used (USGS, 2000; Rogner, 1997; Laherrere, 2001).
  3. Specify MEA oil production.
  4. Set values of other key parameters.
  5. Run the Scenario-Case.
  6. Copy the results to the Results Module.

A7.1 SELECTING A WEC-IIASA SCENARIO

The IIASA study, *Global Energy Perspectives* (Nakićenović, et al., 1998) produced six alternative, integrated global energy scenarios for the period 1990 to 2100. Key drivers for the scenarios were population, economic growth, and the energy intensiveness of economic output. The six scenarios were built around three general paths: Case A: High Growth, Case B: Middle Course and Case C: Ecologically Driven.

The A scenarios foresee a future of ambitiously high economic growth and technological progress, reflecting the belief that there are “no limits” to human ingenuity. Rates of annual growth in purchasing power adjusted gross domestic product run at about 2 percent for OECD countries and twice that for the developing economies. By 2100, global average GDP per capita exceeds that of even the richest nations today. Three variations on the A assumptions portray different evolutions of energy supply. Scenario A1 foresees abundant oil and natural gas resources. In contrast, in scenario A2 oil and gas are scarce, resulting in a return to reliance on coal. In A3 progress in renewable and nuclear energy allows the near elimination of fossil energy sources by 2100.

There is but one B scenario, representing more moderate economic growth and technological progress. Reliance on fossil fuels is greatest in this scenario. However, lacking the technological progress of the A scenarios, dramatic changes in energy sources are necessary to cope with the depletion of fossil resources after 2020. Oil and gas are able to maintain a significant share of energy markets through 2070 by tapping increasingly into unconventional oil and gas resources.

The two C scenarios are optimistic about technology and additionally assume enormous progress in addressing global environmental problems requiring a high degree of international cooperation. Environmental policies play major roles in shaping the future of energy use in the C scenarios. By 2100, global carbon emissions are reduced to one-third of the base year level. In scenario C1, nuclear power disappears entirely by 2100. In C2, advanced, small-scale, inherently safe nuclear reactors are assumed to play a major role in electricity production.

Tables and graphs illustrating the six scenarios are contained in the Scenario Generator Module. These enable the WESM user to compare the alternatives and to choose one that most closely approximates the scenario desired. Once a WEC-IIASA scenario has been chosen, it can be modified and calibrated.

A7.2 MODIFYING A SCENARIO

It is envisioned that five types of modifications to scenarios could be made by changing:

1. economic growth rates,
2. population growth rates,
3. rates of energy intensity changes,
4. patterns of energy use by energy source, and
5. calibration to a base year or reference projection.

In the initial version of the model the rates of change in energy intensity can be modified, and scenarios can be calibrated to year 2000 or to one of three IEO forecasts.

Once a Scenario has been generated, the linked Resource Accounting Module automatically calculates resource depletion and initial long-run oil prices. These are linked to the Oil Market Module that calculates market equilibrium supplies and demands. These return to the Resource Accounting Module that carries out the final resource depletion calculations.

A7.3 INPUTTING CHAMPAGNE MODEL CASES

A Base Case and up to three Alternative Cases of Champagne Model runs for Canada and the United States can be stored in the North American/Conversion Module. The transportation summary energy use table (____) must be pasted into the North American/Conversion worksheets.

A7.4 CALIBRATING A SCENARIO TO CREATE A CASE

The Customized IIASA/WEC Scenarios are calibrated to the North American Champagne Cases by selecting the “Run Case” option in the Output Module. The result is a set of Cases that, for North America, force the Scenario primary and final energy use to match the Champagne model results. The resulting data are linked to the Oil Market Module where a new equilibrium between world oil supply and demand is automatically calculated.

A7.5 EQUILIBRATING AN OIL MARKET CASE

The differences in North American oil use embodied in the Champagne Model Scenario-Case are represented in the Oil Market Model as shifts in the annual North American demand curves. The shifted demand curves are used to calculate a new oil market equilibrium. Once the Oil Market equilibrium has been established, the depletion of conventional and unconventional oil resources is automatically updated in the Resource Accounting Module.

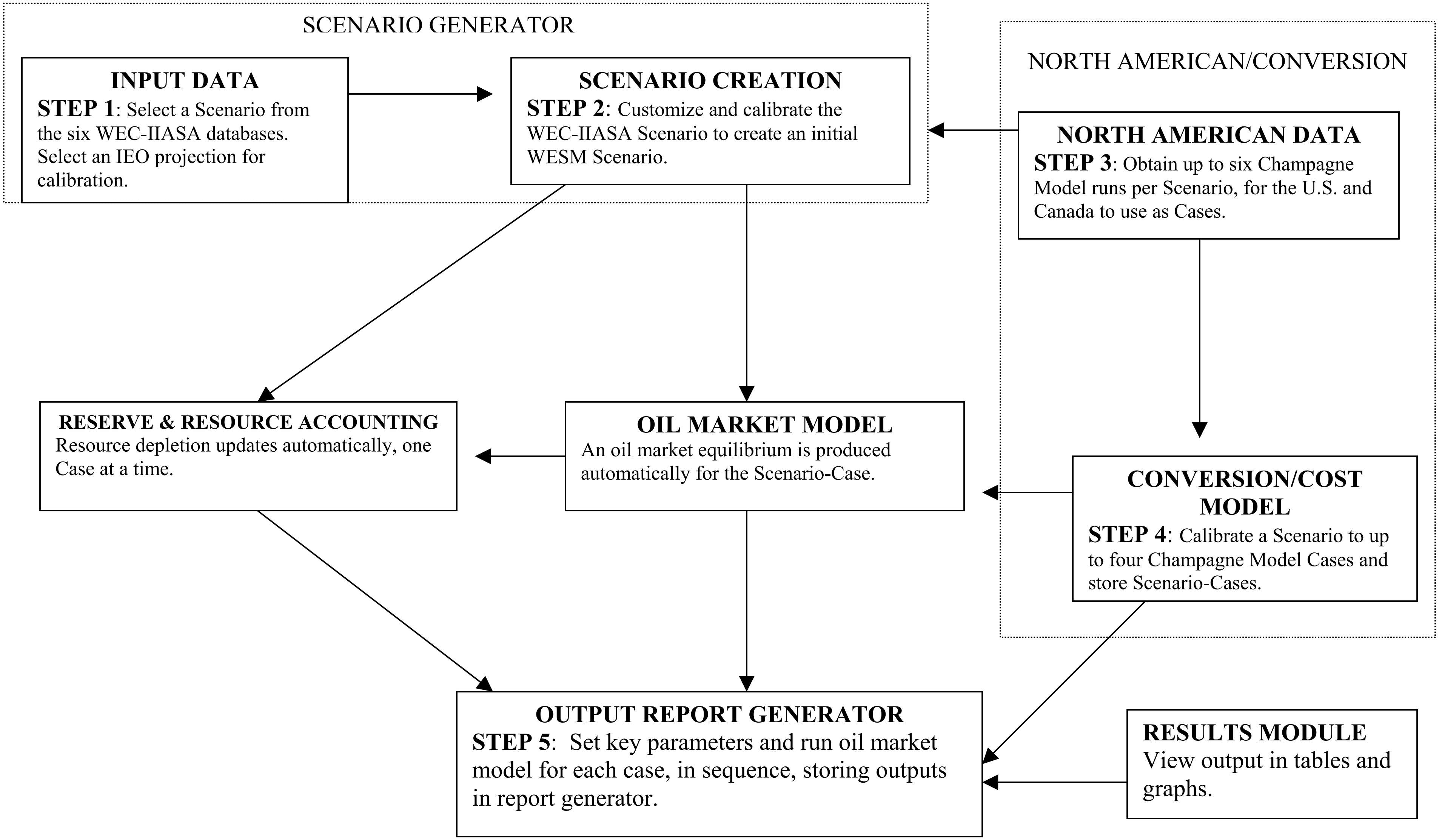
A7.6 GENERATING AN OUTPUT REPORT

A8. CONCLUSIONS

The World Energy Scenarios Model provides the capability to analyze the depletion of conventional oil resources and the transition to unconventional resources under a variety of global energy scenarios and a variety of assumptions about resource availability and utilization. With this version of the model it is possible to analyze how various factors will affect the timing of the peaking of conventional fossil fuel use, and the rate of transition to unconventional petroleum.

The initial implementation also permits analysis of the implications of conventional oil resource depletion on OPEC’s position in the world oil market. In particular, price shocks can be simulated by restricting OPEC production, and their impact under alternative Scenario-Cases can be calculated and compared.

WORLD ENERGY SCENARIOS MODEL



SCENARIO GENERATOR

INPUT DATA
STEP 1: Select a Scenario from the six WEC-IIASA databases. Select an IEO projection for calibration.

SCENARIO CREATION
STEP 2: Customize and calibrate the WEC-IIASA Scenario to create an initial WESM Scenario.

NORTH AMERICAN/CONVERSION

NORTH AMERICAN DATA
STEP 3: Obtain up to six Champagne Model runs per Scenario, for the U.S. and Canada to use as Cases.

RESERVE & RESOURCE ACCOUNTING
Resource depletion updates automatically, one Case at a time.

OIL MARKET MODEL
An oil market equilibrium is produced automatically for the Scenario-Case.

CONVERSION/COST MODEL
STEP 4: Calibrate a Scenario to up to four Champagne Model Cases and store Scenario-Cases.

OUTPUT REPORT GENERATOR
STEP 5: Set key parameters and run oil market model for each case, in sequence, storing outputs in report generator.

RESULTS MODULE
View output in tables and graphs.

INSTRUCTIONS FOR EXECUTING A WESM RUN

All of the WES files should be copied to the same directory.

5 spreadsheets are required:
Scenarios.xls (allows you to select a IIASA-WEC Scenario)
ConversionCost.xls
OilMarketModel.xls
Output.xls
ResourceAccounting.xls
Results.xls (temporary results file)

Procedures for executing a run.

1. Open Scenarios.xls. (Graphs comparing the scenarios are available on the comparisons page. Set the annual rate of change in energy intensity (values highlighted in yellow). There are two options:
    a. Use IIASA-WEC Scenarios calibrated to Y2000 (select any of the scenarios)
    b. Use IEO-EIA forecast data to 2020 splined to IIASA-WEC data.
        i. Select the IIASA-WEC case
        ii. Select the IEO Case (Reference, High Growth, Low Growth)
        iii. Use IEO forecast
2. Output data from the US and Canada Champagne runs is now in the Conversion Cost Spread Sheet. Copy data directly from the Champagne Output page (B2-Outputs). The table we are using is under Part E. Summary of Energy Use and GHG Emissions…. Total Energy Use (petajoules). Paste As Values. (Currently we only have "real" data for the Reference Case and Greening the Pump).
3. Open the following Workbooks:
    a. ConversionCost.xls
    b. OilMarketModel.xls
    c. Output.xls
    d. ResourceAccounting.xls

    NOTES:
    If you open the Output.xls file before you open the OilMarketModel.xls and ConversionCost.xls files, you will get an error when you attempt to update the links.
    If you are starting a new set of cases you may want to run the ClearResults macro from the "Parameters and Controls" page to clear the results file of old data. Be sure you have saved the "old results" to a file with a new name.

4. The model is run from the "Parameters and Controls" page in the Output Spreadsheet. Select either the Reference Case or the Greening the Pump Case. Edit the parameters in the "Parameters and Controls".

5. Select oil resource data source (Rogner , USGS or Laherrere).
6. (The button labeled “Use IIASA Production Data” will insert the Middle East Production data from the selected scenario.)
7. Once the parameters are set, click on “Run Base Case”. This sets the base case in the ConversionCost workbook
8. Check the field labeled “Sum of Differences”
9. The Save Process is “Two Step”. Once you have finished with a particular case it can be copied to the Results file. Once you have finished with a group of related cases you can save them either by manually saving Results.xls or by clicking on the button “Save Results.xls as…”
10. To save the results, click on “Copy Current Case to Results.xls”.
11. To run additional cases based on the same parameters and base case, click on the buttons to the left. Be sure to copy the results to the results file once you are finished with a case.
12. Once you are finished with a set of cases click on “Save Results.xls as” to save the results file to a new file or just open and save the Results file under a new name.
13. If you want to start a new set of runs click on “Clear Results” to clear the old data. (Be sure you’ve saved the old results first!)

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