TOPIC PAPER #10

GEOLOGIC ENDOWMENT

On July 18, 2007, The National Petroleum Council (NPC) in approving its report, *Facing the Hard Truths about Energy,* also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the Task Groups and their Subgroups. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached Topic Paper is one of 38 such working document used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix E of the final NPC report provides a complete list of the 38 Topic Papers and an abstract for each. The printed final report volume contains a CD that includes pdf files of all papers. These papers also can be viewed and downloaded from the report section of the NPC website (www.npc.org).

NATIONAL PETROLEUM COUNCIL

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Geologic Endowment

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Abstract:

This chapter will focus on the liquid hydrocarbons that are within the Global Hydrocarbon Endowment, but will also discuss natural gas:

- the major types of hydrocarbons;
- global hydrocarbon petroleum endowment;
- classify volumes as proved reserves or resources estimates,
- explain the differences between conventional and unconventional resources,
- list methods used to make the estimates, and
- provide elements for best practice future estimates.

1.0 Why we do endowment assessments

Oil and natural gas resource assessments fill a variety of needs for consumers, policy makers, land and resource management agencies, investors, regulators, and industry planners, to name just a few. Consumers, given a choice, will not want to depend upon a resource that is scarce or will not be readily available for an acceptable price in the near future. Individual governments utilize resource assessments to exercise responsible stewardship on public lands, to estimate future revenues to the government, and to establish energy, fiscal and national security policy. The petroleum industry and the investment community use resource estimates to establish corporate strategy and make investment decisions. Regulatory organizations, such as government energy ministries, corporation commissions, and the Minerals Management Service of the U.S. Department of the Interior utilize resource estimates in designating acreage for leasing and drilling. Thus, the fundamental value of resource assessments can be seen in many aspects of the community.

1.1 Types of Hydrocarbons

Petroleum is a collective term for hydrocarbons in the gaseous, liquid, or solid phase, in other words, natural gas, crude oil, natural gas liquids (NGL), and tar. The Global Hydrocarbon Endowment includes the following: crude oil, natural gas, and natural gas liquids (condensate). Following are definitions for the different forms of liquid petroleum.

CRUDE OIL is defined as a mixture of hydrocarbons that exists in a liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separation facilities (American Petroleum Institute, 1995 (API)).

Oil is mainly a mixture of complex hydrocarbon compounds, having carbon/hydrogen ratios ranging typically from 6 to 8.

Oil has specific gravities ranging typically from 0.76 (55º API gravity) to 1.00 (10º API gravity). API gravity, defined by the American Petroleum Institute, is a measure of the density of oils.

Crude oil is refined to produce a wide array of petroleum products, including heating oils; gasoline, diesel and jet fuels; lubricants; asphalt; ethane, propane, and butane; and many other products used for their energy content or chemical attributes.

NATURAL GAS LIQUIDS (NGLs) are those portions of the hydrocarbon resource that exist in gaseous phase when in natural underground reservoir conditions, but are liquid at surface conditions (that is, standard temperature and pressure conditions; 60º F /15º C and 1 atmosphere). These NGLs are separated from the gas and liquefied at the surface in lease separators, field facilities, or gas processing plants (American Petroleum Institute, 1995).

PETROLEUM LIQUIDS are undifferentiated oil and natural gas liquids.

NATURAL GAS is a mixture of hydrocarbon compounds existing in the gaseous phase or in solution with oil in natural underground reservoirs at reservoir temperature and pressure conditions and produced as a gas under standard temperature and pressure conditions (American Petroleum Institute, 1995). Natural gas is principally methane, but may contain ethane, propane, butanes, and pentanes, as well as certain non-hydrocarbon gases, such as carbon dioxide, hydrogen sulfide, nitrogen, and helium.

Natural gas can be associated with or dissolved in oil accumulations (called 'associated' or 'dissolved' gas') or not associated with any liquid hydrocarbons (called 'non-associated' gas'). Associated gas is free natural gas, commonly known as gas-cap gas, which overlies and is in contact with crude oil in the reservoir. Dissolved gas is natural gas in solution with crude oil in the reservoir at reservoir temperature and pressure conditions (American Petroleum Institute, 1995). Associated/dissolved gas is often re-injected into the reservoir to maintain a pressure drive for oil production and may therefore not be an economically feasible resource in a near-term assessment time frame. Nonassociated gas is free natural gas that is not in contact with crude oil in the reservoir (American Petroleum Institute, 1995).

Oil and gas accumulations are usually treated separately in the assessment process. Gas/oil ratios (GOR) are calculated for each accumulation to identify the proportions the two major commodities (oil or gas). An oil accumulation is commonly defined as having a GOR less than 20,000 cubic feet of gas/barrel of oil; a gas accumulation is defined as having a GOR equal to or greater than 20,000 cubic feet of gas/barrel of oil.

What is not included in this overview

- Petroleum liquids that are manufactured from naturally-occurring mined **solids** using a thermal or dilution process:
  Oil Shale (kerogen)
  Oil Sands (bitumen)
  Coal-to-Liquids products.

- Liquid fuels extracted from agricultural products:
  Biodiesel from vegetable oil
  Ethanol from sugar cane, corn, or switchgrass.

- Petroleum liquids condensed from **dry natural gas** using a cryogenic process:
  Liquefied Natural Gas (LNG)
  Gas-to-Liquids products.

1.11 Hydrocarbon Formation

While the processes that generate oil and gas are active today, the amount generated annually represents only a tiny fraction of the amount extracted for consumption. For all practical purposes, the total amount of the world's hydrocarbon resources – its endowment – is finite. The endowment is a collection of many, many individual petroleum accumulations. These accumulations come in many shapes and sizes and many of which are finely compartmentalized.

The *individual attributes* that describe a single accumulation are also each quite variable, but each has some basic components (Figure 1):

- Hydrocarbons are generated in "kitchens" (underground areas where temperature is sufficiently high) from strata containing high concentrations of organic material called *source rocks.* The degree to which the source rocks have been heated, and the types of organic material in the source, control the type of hydrocarbon generated; some source rocks yield gas and some yield oil. "Cooking" in the "kitchens" generally leads to expulsion of hydrocarbons from the source rocks, with oil formed at lower states of thermal maturity than gas.
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- Once expelled, the hydrocarbons can *migrate* upward toward rocks of lower pressure. During this migration, large quantities are commonly lost along the way, often leaving behind in a trail of small accumulations. In some cases, hydrocarbons do not migrate and remain instead in the source rocks.

- During migration, large volumes may find their way to a *reservoir*, which has *trapping boundaries* of sufficient size and strength to catch and hold most or all the hydrocarbons that migrate into it, and is capped by an impermeable layer called a *seal rock*. Reservoirs can be formed from many different rock types and can therefore be quite variable, with different pore sizes, permeability, residual water, and other rock attributes, all of which influence the proportion of hydrocarbons which may one day be recovered *if* the accumulation is discovered and *if* the available technologies and prevailing economic environment favors development and production. These variable attributes also affect the extraction techniques applied, and success of eventual production.

- Finally, all of these individual attributes - source deposition, maturation, expulsion, migration, reservoir deposition and trap formation and filling – must have taken place in the *correct sequence*; and the trapping elements of the accumulation need to have been maintained through time, often tens of millions of years – for instance, the traps cannot have been compromised (opened) by movement of rocks in the subsurface or by erosion on the surface after the hydrocarbons have been trapped there.

Figure 1. Elements of a petroleum system (from AAPG Slide Bank).

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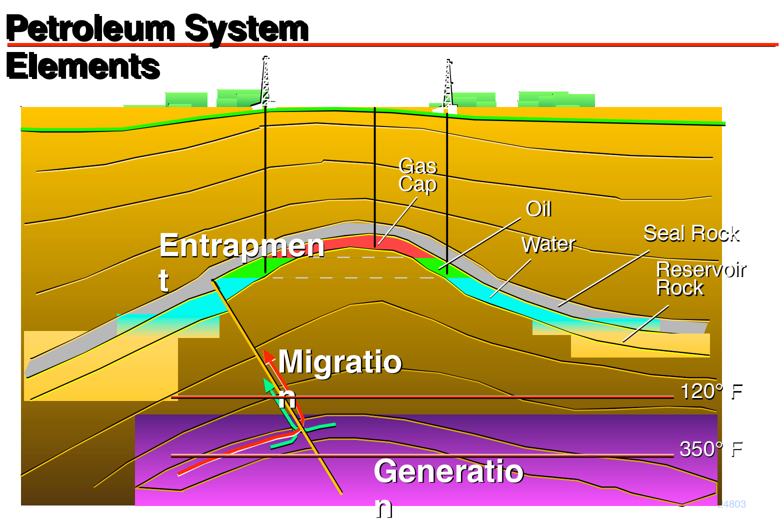


1.2 Global Liquid Hydrocarbon Endowment Estimates - Defined

The global liquid hydrocarbon endowment is the sum of those liquid volumes already produced *(cumulative production)*, those volumes already known to be or assumed to be recoverable *(reserves and resources)*, and those additional volumes in-place that are not recoverable by any current means (unrecoverable in-place volumes), but may technically and economically recoverable in the future.

Figure 2 is a graphical representation of the classification system jointly adopted in March 2007 by the Society of Petroleum Engineers (SPE), World Petroleum Council (WPC), American Association of Petroleum Geologists (AAPG), and the Society of

Petroleum Evaluation Engineers (SPEE). This system was developed over a three-year period and incorporated input from the four sponsors, the international mining community, the International Accounting Standards Board (IASB), and the United Nations.

The system defines the major recoverable resources classes: Production, Reserves, Contingent Resources, and Prospective Resources, as well as Unrecoverable petroleum. Resources (including reserves) are classified as undiscovered, discovered-subcommercial, or discovered-commercial. Resources are further categorized over the range of uncertainty. Since the categories have been defined only in their final form in 2007, data available around the world often do not yet fit these definitions.

Figure 2. Portions of the hydrocarbon endowment, as defined in the 2007 SPE/WPC/AAPG/SPEE resources classification system.

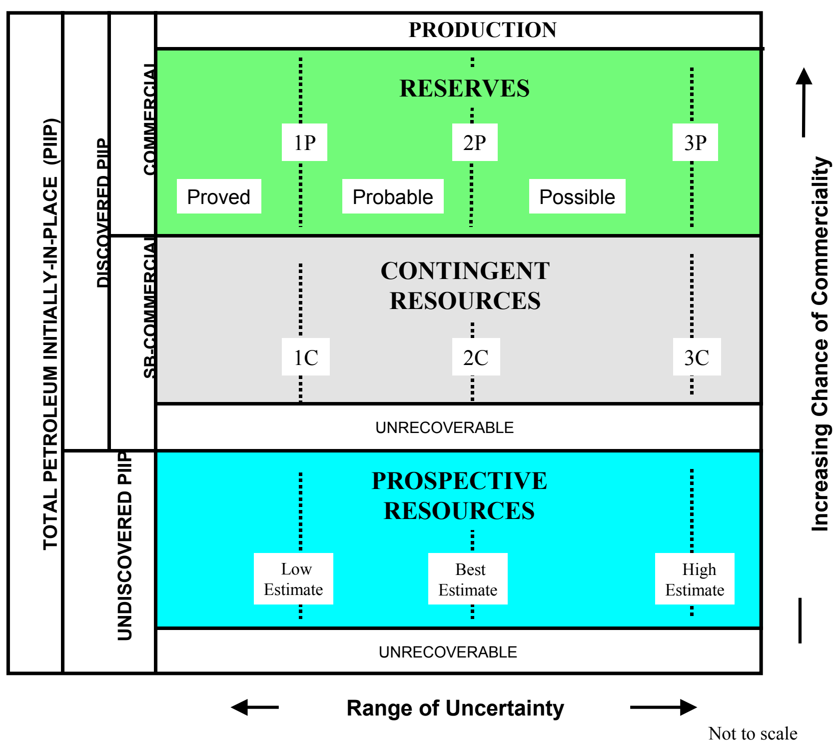


Table 1, below, lists the estimates of the technically recoverable Global Liquid Hydrocarbon Endowment of conventional resources (oil plus natural gas liquids) by component, in billion barrels, as of 2000 (USGS, 2000). ([1]Reserve and cumulative production data are not global numbers, but rather, reflect only those parts of the world actually assessed by USGS. Reserve and cumulative production data are from Petroconsultants (1966) and NRG Associates (1995). F95 represents a 95 percent chance of at least the amount tabulated. F5 represents a 5 percent chance of at least the amount tabulated.)

	F95	Mean	F5
Undiscovered	495	939	1,589
Reserve growth		730	
Remaining reserves[1]		959	
Cumulative production[1]		717	
		3,345	

The sum of remaining producible volumes in discovered accumulations plus undiscovered volumes is often called *remaining resources.* These volumes, their geographical distribution, and the sizes of the accumulations in which they will occur, are of greatest importance to strategy and policy decisions.

The U.S. Geological Survey (USGS) World Petroleum Assessment 2000 estimates for undiscovered potential were chosen as the basis of the NPC study. There are several reasons for this: (1) one of the missions of the USGS is to provide estimates of the national (onshore and offshore State-controlled waters; MMS does Federal U.S. offshore, and the USGS WPA 2000 incorporated the most recent estimates from the MMS) and world endowment of geologically based energy resources, (2) the USGS methodology is geologically based, statistically rigorous, and has been peer reviewed (http://energy.cr.usgs.gov/oilgas/noga/methodology.html), (3) USGS has access to data on a global basis, (4) USGS is viewed as unbiased, with no land, resource, or fiscal responsibilities for energy resources, (5) the method, assumptions, and data are transparent and well documented, and (6) results are publicly available.

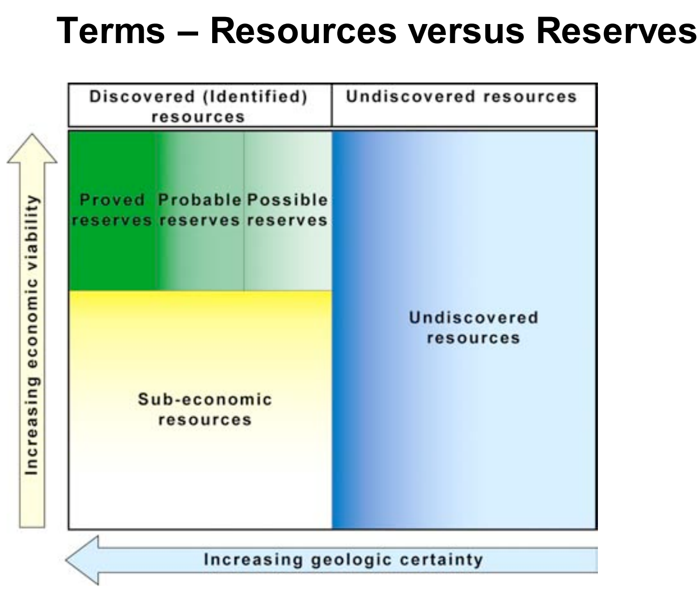
1.21 Reserves versus Resources

Reserves and resources form the strategically important constituents for remaining endowment, and are explained and contrasted in this section. In general, the term 'reserves' deals with recoverable, commercial volumes associated with known fields, and 'resources' is a broader, more inclusive, term that deals with known and undiscovered petroleum accumulations. In general, there is increasing geologic certainty and economic viability as one moves from resources to reserves (Figure 3). The situation is complicated, however, by the fact that some companies delineate the 'highest risk' volumes in fields as 'contingent resources,' and the industry term for remaining hydrocarbons (remaining resources) also includes reserves volumes. In the following discussion, unless noted otherwise, we will discuss petroleum reserves and resources using the following definitions:

RESERVES are those estimated quantities of petroleum anticipated to be commercially recoverable from known accumulations from a given date forward under defined conditions (such as prevailing economic conditions, operating practices, and government regulations). Reserves must satisfy four criteria: they must be *discovered*, *recoverable*, *commercial*, and *remaining* based on the development project(s) applied. Reserves are further subdivided as Proved (P90, 1P), Possible (P50, 2P), or Probable (P10, 3P) in accordance with the level of certainty associated with the estimates and their development and production status.

RESOURCES are those quantities of petroleum estimated, as of a given date, to be potentially recoverable from known or undiscovered accumulations. Resources are not considered commercial at the time of estimation. Resources are classified, by some, as Contingent or Prospective Resources depending on whether the accumulation is known or undiscovered.

Figure 3. Example of a McKelvey diagram, used to illustrate the distinction between resources and reserves (modified from USGS Circular 831, 1980).



1.22 In-place Resources

It is evident from the preceding definitions that oil and gas reserves and resources in known or yet to be discovered accumulations represent only the recoverable portion of the oil or gas-in-place that these accumulations hold at a given time. It is physically impossible to recover 100 percent of the oil and gas-in-place, but every producer strives to recover as much as possible. Indeed, improved recovery factors are one reason for Reserves "Growth" as discussed below in section 1.25, below.

Thus, knowing the amount of hydrocarbons-in-place that are present in an accumulation or in all accumulations in the world is of significance, if one wants to quantify the local or the global petroleum endowment. Schollnberger (1998a) attempted to do this (Table 2). Looking forward to the beginning of the year 2101, Schollnberger used Amoco's (proprietary) worldwide database, USGS data, BGR (German) data, as well as data from Petroconsultants (now IHS) and Nehring. Schollnberger distinguished three cases: the "high case" assumes "another hydrocarbon century" with no environmental constraints on petroleum products, that acreage is available for leasing and development, and that the economic considerations are conducive to oil and gas development. The "low case" assumes "the end of the internal combustion engine" around 2035, environmental constraints and economic conditions adverse to hydrocarbon development. The "most likely case" assumes conditions between the two extremes, with other energy sources gradually replacing oil and gas. These cases were built using the following recovery factors, thought to be viable for recovery in 2102:

High case
- Conventional oil – 55%, heavy oil 30%, gas – 80%, tight gas – 35%

Low case
- Conventional oil – 35%, heavy oil – 10%, gas – 60%, tight gas – 30%

Mostly likely case
- Conventional oil – 45%, heavy oil – 20%, gas – 70%, tight gas – 30%

In this analysis, oil includes conventional, heavy, and very heavy oil and natural gas liquids, but does not include oil that is first converted and then extracted from oil shales. Gas includes "tight" gas and coalbed methane, but does not include gas from gas hydrates.

Schollnberger (1998a) estimates the petroleum initially-in-place in all accumulations throughout the world recognized through the end of the year 2100 as follows:

Table 2. Global in-place petroleum resources for three "cases" (Schollnberger, 1998a).

High Case	
Oil	15,520 gigabarrels
Conventional and ngl's	8,516
Heavy oil	7,002
Gas	8,600 gigabarrels oil equivalent
Conventional gas	5,232
Tight gas	3,373
Low Case	
Oil	13,410 gigabarrels
Conventional oil	8,340
Heavy oil	5,070
Gas	6,210 gigabarrels oil equivalent
Conventional gas	4,952
Tight gas	1,256

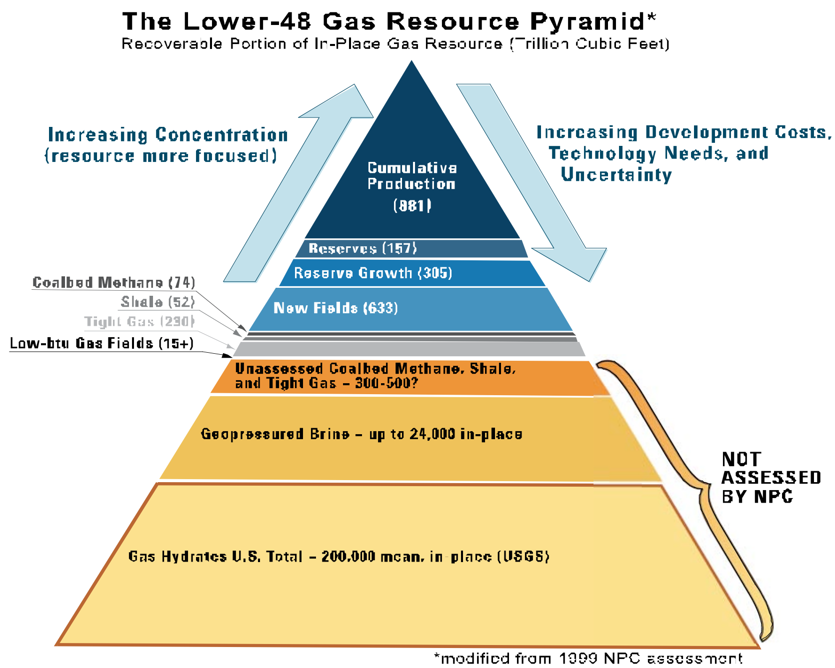
Most Likely Case	
Oil	14,960 gigabarrels
Conventional oil	8,347
Heavy oil	6,613
Gas	8,000 gigabarrels oil equivalent
Conventional gas	5,048
Tight gas	2,954

While these volumes can only be rough estimates, they indicate that the petroleum endowment potentially available is truly large. However, the extent to which this endowment can be technologically recovered, and can be done so on a commercially viable basis, is still very much open to question. Only a portion of these resources will be recoverable for use.

1.23 The Resource Pyramid Concept

The various volume types discussed above – produced volumes, reserves, recoverable and currently unrecoverable resources – can be visualized as a *resource pyramid* (Figure 4). The small, top portion of the pyramid represents the volumes which have already been produced. The upper middle of the pyramid represents those resources which have been discovered and are known to occur. The lower middle of the pyramid represents resources which are predicted to exist and which have not yet been discovered. Finally, the bottom portion of the pyramid represents those resources which are known or hypothesized to exist but which are not recoverable by any current means. Figure 4 is an example of such a pyramid, for natural gas resources in the lower 48 states of the United States (NPC, 2003). Cumulative production is represented at the top of the pyramid, and unconventional natural gas from gas hydrates is represented at the bottom of the pyramid. In between the two are resources that represent varying degrees of technical and economic accessibility.

Figure 4. Resource pyramid of natural gas in the lower 48 states of the United States (NPC, 2003).



The uppermost portion of the pyramid are those resources that are brought to market first (cumulative production, in the pyramid above). In countries such as the United States, where acreage was relatively accessible to the oil and gas industry during the last 150 years, these resources are generally the most obvious to find, and before 1910 they were often discovered at shallow depths (less than 3000 ft). Over time, improved methods allowed for the development of deeper and deeper reservoirs and the application of ever more sophisticated seismic methods allowed for the delineation of deeper and more complex fields. As a result of these and other technical innovations, new portions of the resource endowment (represented in these figures by the lower portions of the resource pyramid) become viable making available hydrocarbon resources that were previously uneconomic. One role of new technology is to change which resources are economically viable and therefore ultimately recoverable. In addition, as infrastructure or commercial frameworks are put in place, previously uneconomic resources may become economic.

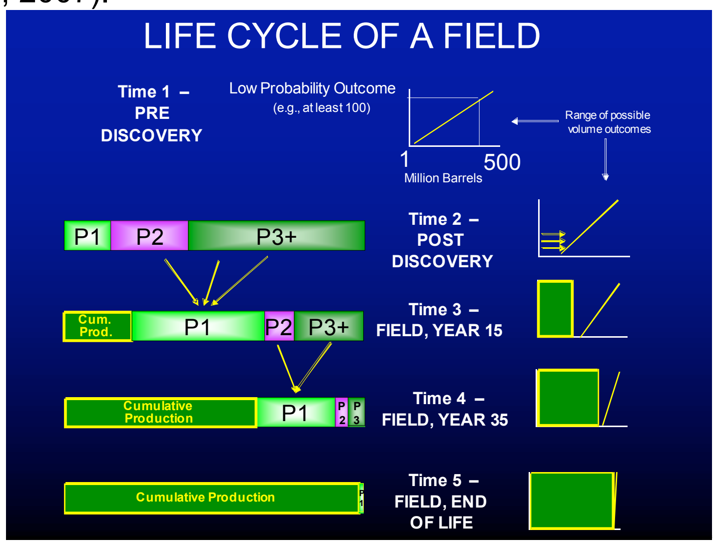
However, there are many portions of the world where access to acreage has been restricted by government (e.g., Norway) or the appropriate technologies were not applied or both (e.g., the former Soviet Union, China, etc.), or companies have decided not to pursue exploration or development. In these areas, the top of the pyramid represents what was found under these restrictions and large oil and gas discoveries may still be possible in the future from the lower parts of the pyramid.

Developments in technology as well as geologic understanding can make previously unconventional and uneconomic resources economic and viable. There are many examples of this progression, including the development of tight gas and shale gas reservoirs, fractured shale oil reservoirs, coalbed gas, deeper and more subtle conventional targets, and offshore deep water development.

1.24 Reserve Categories and Reserve Conversion through Time

Oil and gas fields go through life cycles, as illustrated below in the Figure 5.

Figure 5. Graphical representation of the life cycle of an oil field (from Jeff Brown, 2007).



During exploration for hydrocarbons, geoscientists prepare an estimate of the range of possible volumes that could be contained in an undrilled (untested) possible accumulation (called a *prospect*), if hydrocarbons were to be found. The amount of *uncertainty* in that pre-discovery estimate – the range of possible volume outcomes, given success – can be dauntingly large. This uncertainty is often portrayed in the form of a probability plot, as shown at the top of Figure 5. Note that the range of possible outcomes shown in Figure 5 (Time 1), ranging from 1 to 500 million barrels, would be reasonable for a typical prospect, and that the chance of getting a very large discovery (for instance, 100 million barrels or more) is very small.

Once a test well (called a *wildcat* well) has been drilled and proves the presence of hydrocarbons (Time 2 in Figure 5) significant uncertainty still remains as to the overall volumetric potential of the field, both in terms of the sizes of the accumulations and the number of the accumulations. Generally, additional wells are drilled (*delineation wells*) to determine the limits of the accumulation. This information is used to determine if the accumulation is sufficiently large to become a productive field, the number of wells necessary to effectively and efficiently produce that field, the optimal location and scale of a central production facility, and export pipeline size,.

Note that, for the different time periods in Figure 5, the width of the bar, which represents the ultimate volume that will be produced from the field, is subdivided into different pieces labeled P1, P2, etc. These labels reflect industry-accepted abbreviations for different categories of *reserves*, also called ‘remaining reserves,’ which are defined as volumes of oil that can reasonably be expected to be produced over the productive life of the field, based upon current technological and economical conditions. The major classification subdivisions for reserves are (SPE/AAPG/WPC/SPEE Petroleum Reserves and Resources Classification):

PROVEN (P1) – Proved Reserves are an incremental category of estimated recoverable volumes associated with defined technical uncertainty. Proved reserves are those quantities of petroleum which, by analysis of geological and engineering data, can be estimated with reasonable certainty to be commercially recoverable, from a given date forward, from known reservoirs and under defined economic conditions, operating methods, and government regulations. Proved Reserves can be categorized as Developed or Undeveloped. If deterministic methods (see below) are used, the term “reasonable certainty” is intended to express a high degree of confidence that the quantities will be recovered. If probabilistic methods (see below) are used, there should be at least a 90% probability that the quantities actually recovered will equal or exceed the estimate.

PROBABLE (P2) – Probable Reserves are an incremental category of estimated recoverable volumes associated with defined technical uncertainty. Probable Reserves are additional Reserves that are less certain to be recovered than Proved Reserves. It is equally likely that actual remaining quantities recovered will be greater or less than the sum of the estimated Proved plus Probable Reserves. In this context, when probabilistic methods are used, there should be at least a 50% probability that the actual quantities recovered will equal or exceed the Proved + Probable estimate.

POSSIBLE (P3) – Possible Reserves are an incremental category of estimated recoverable volume associated with defined technical uncertainty. Possible Reserves are those additional Reserves that are less certain to be recovered than Probable Reserves. It is believed unlikely that the actual remaining quantities recovered will equal or exceed the sum of Proved plus Probable plus Possible Reserves being the high estimate scenario. In this context, when probabilistic methods are used, there should be at least a 10% probability that the actual quantities recovered will equal or exceed the Proved + Probable + Possible estimate.

Note that, immediately after discovery, a very small portion of the field’s ultimate productive volume can be called ‘proven.’ There are very stringent rules defining what can be designated ‘proven;’ these rules are currently in a state of revision, and providing details for the definitions goes beyond the scope of this chapter. What is important is that, through time, the categorization of volumes in an oil field changes – Possible and Probable reserves can be converted to the Proven category, and then these Proven reserves are depleted (increasing Cumulative Production).

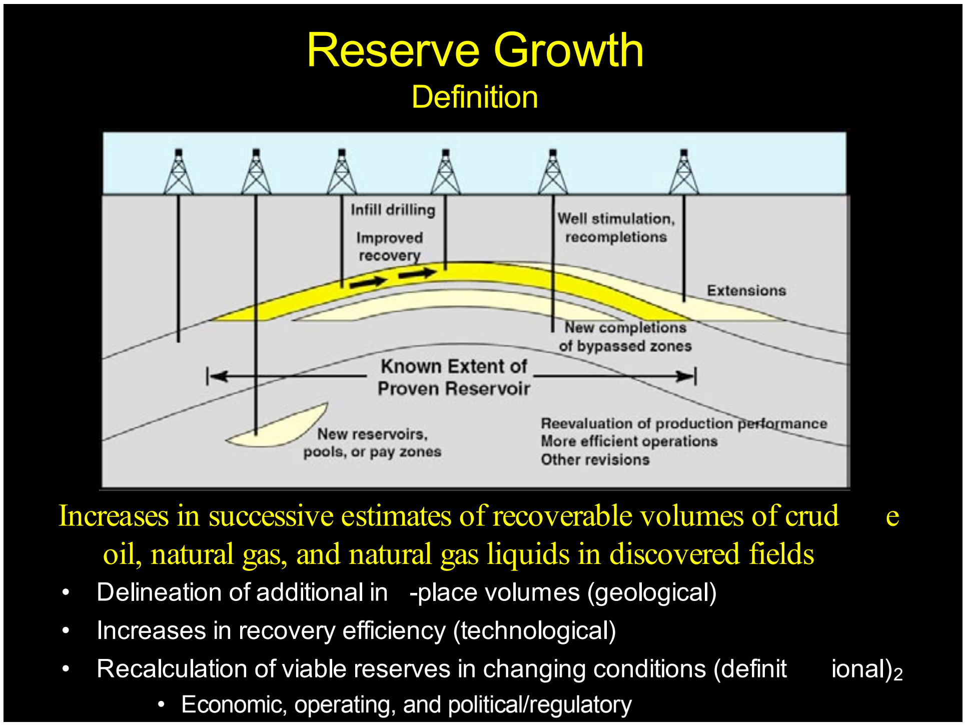
1.25 Reserves "Growth"

'Field growth' or 'Reserves Growth' is the increase in total proved reserves of an existing field through time. The term 'reserves growth' is a bit of a misnomer, a concept that stems from the observation that the estimated potential ultimate recoverable volume of a given field (field 'size') tends to grow larger through time. In theory, as volumes in a field are produced, the estimates of how much remains to be produced in the future should decrease, as illustrated in Figure 5. However, often the reported remaining reserves remain flat, or even increase. The impact of this on future resource assessments is that, if currently reported field reserve volumes are summed, the aggregate volume will likely underestimate remaining volumes.

Reserve growth is defined as the increase in successive estimates of recoverable crude oil, natural gas, and natural gas liquids and condensates in discovered fields. Reserves grow for a variety of reasons including extending current field boundaries both internally by in-fill drilling and outward by satellite development, advances in drilling or production technology, advances in exploration technology (such as 3-D and 4-D seismic), and advances in our geologic and engineering understanding of the petroleum reservoirs (Figure 6).

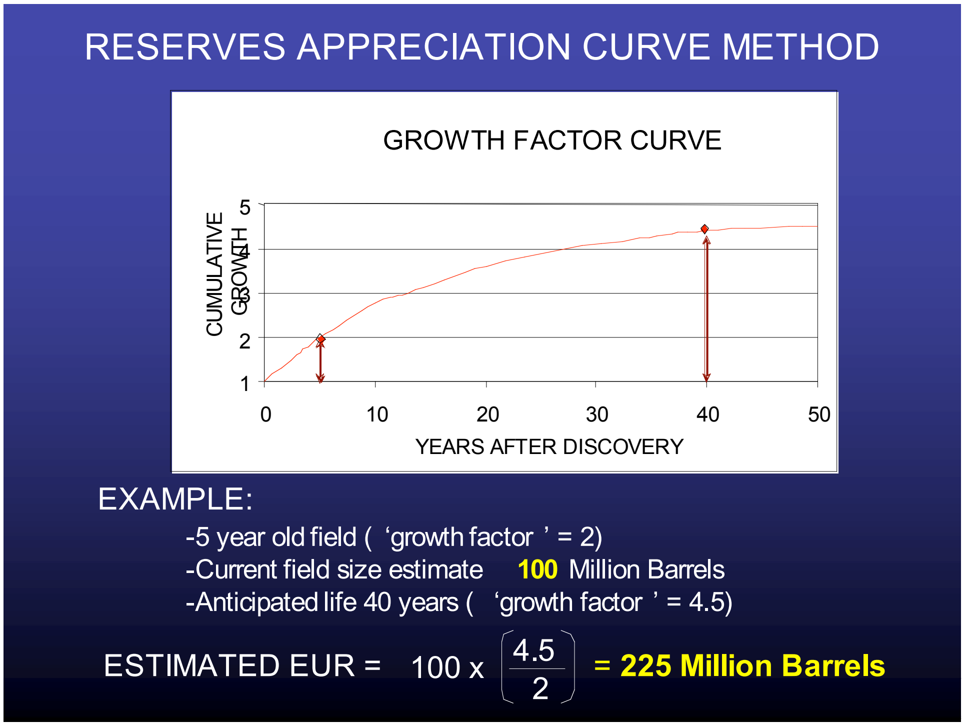
Field growth occurs in almost all petroleum provinces in the world and is considered the most important source for additional reserves in the United States. Additions to reserves from reserve growth are volumetrically significant in petroleum assessments. Most additions to world reserves in recent years are from growth of reserves rather than new discoveries. The USGS recently estimated that the worldwide volume of oil and gas added by reserve growth exceeded volumes of new discoveries by about 3 to 1 from January 1996 and December 2003 (Klett and others, 2005). Reserves growth has factored significantly into the methods used by the USGS and others to estimate resource endowments and potentially recoverable volumes. By studying the volume estimates at different points in time for mature fields, mathematicians can create 'growth factor curves' such as the one illustrated in Figure 7. These curves can be used to help predict the amount of oil that a field will ultimately produce over its lifetime.

Figure 6. Graphical representation of some causes of Reserve Growth (Gautier and others, 2005).



In the example below (Figure 7), a relatively young field is originally estimated to hold 100 million barrels of producible oil. Analysis of the size growth patterns of similar but older fields in the area has resulted in the generation of a 'type' cumulative growth curve which indicates that, when the field is fully exploited, it will yield an additional 125 million barrels not recognized today. When these 'hidden' volumes are aggregated on a basin or country scale, they can be quite large and of strategic importance.

Figure 7. Reserves appreciation estimation using growth factor curves (from Jeff Brown, 2007).



The concept and importance of reserves growth to estimating available future oil is the subject of considerable debate. One challenge stems from the fact that in some estimates only Proven (P1) reserves are considered, while in others the sum of Proven plus Probable reserves (P1+P2) are taken to reflect 'reserves.' Depending upon the reference point, P1 or P1+P2, the percentage and rates of conversion of reserves (and therefore the predicted amount of field 'growth') is substantially impacted. Another challenge in estimating ultimate recoverable reserves is that today fields are generally (1) smaller, (2) developed more quickly, and (3) developed with better seismic data, than in the past, and so there is some concern that the growth patterns of older fields may not be as robust for recent, and future, discoveries. Studies are underway to try to determine the impact of reserves growth for 21st century fields.

1.26 Undiscovered Resources

Undiscovered petroleum resources consist of resources that are postulated to exist, on the basis of geologic knowledge and theory, outside of known accumulations. As explained above in Section 1.11 (Hydrocarbon Formation), there are many aspects of resource endowment that must be present for hydrocarbons to form and be preserved. In a comprehensive resource assessment, each of these aspects is examined and measured by a variety of geological, geochemical, and geophysical means, yet a great deal of uncertainty remains. These uncertainties are expressed using statistical distributions, or ranges for possible outcomes, to capture a description of what future accumulations in a geologic play, basin, or country might look like. Construction of these distributions is guided by analysis of fields that have already been discovered, and by examining the geology of the region. Examination of size characteristics of *known accumulations*, together with an analysis of how many have already been discovered, is used to project numbers and sizes of those which may remain to be discovered. This analysis is the general manner in which undiscovered resources are estimated. Often, when there are no data existing in the basin or region under study, *analogues* to known petroleum regions are used, and the characteristics and properties from the analogues are used to estimate the resources.

Industry continues to discover significant new resources. Yet every petroliferous basin is endowed with a finite population of potential traps that might hold accumulations. Historically, about 1 in 4 traps have proven to be viable (IHS, 2000) in the case of conventional resources. This ratio has remained remarkably constant, on a global scale, since the 1960's, but may not be applicable to continuous resources, discussed below. The exploration and production process therefore is one involving sampling this finite population without replacement. Once a structure is tested, it is removed from the population of potential future discoveries. Not surprisingly, the larger and more obvious potential traps are usually drilled first, and usually the largest discoveries are made early in the 'life' of a basin or play. This is the reason that the fields being discovered today are smaller, in general, than those discovered and developed in the past. However, there are significant exceptions to this generality and very large fields continue to be found, especially where acreage availability was restricted in the past or in frontier areas where there has been little exploration.

The predicted volumes to be found in the undrilled population of potential accumulations reflect estimated *undiscovered resources*. These estimates must take into account the average prospecting success rate, number of undrilled remaining prospects, and the predicted size characteristics for the future discoveries. While the methods for estimating how much oil remains to be found in a basin will be discussed in detail later in this chapter, results of such analyses carry a much greater uncertainty (wider range of volumetric outcomes) than the uncertainty associated with remaining reserves in existing fields because there is much less data on which to base the estimate.

1.27 Conventional versus Unconventional Reserves and Resources

Until the 1990's, virtually all estimates of global hydrocarbon endowment focused on reserves and resources that were called 'conventional' – oils and condensates (liquids that were extracted during production from gas fields) and gas that could be expected to be economically produced using state-of-the-art technology, and which were distributed in nature as discrete accumulations. But "state-of-the-art" is a moving target. For instance, it was common practice as recently as the 1990's to exclude estimates for liquids located in water depths greater than 1000 meters, where significant production now exists.

Under most contemporary definitions, the primary delimiter between 'conventional' and 'unconventional' liquids is viscosity, that is, a fluid's resistance to flow. Enormous deposits of potentially productive liquid hydrocarbons exist in nature that cannot flow under either reservoir or surface conditions – an unconventional resource. This category includes huge deposits of low viscosity oil in Venezuela and western Canada, and bitumen deposits (tar-impregnated sands) in western Canada. The volumetric potential of these deposits may dwarf that of conventional accumulations. These resources in Canada are now economically produced and traded on the stock market. As a result of Canada's focus on their 'unconventional' resources, they now have the second largest reserves of oil in the world. Even though these resources are often difficult and expensive to produce (where such deposits are near the earth's surface, they are mined using techniques similar to those used for coal deposits; deeper deposits are subject to super-heated steam or solvent injection), their potential make them an attractive target to pursue.

The following definitions reflect these viscosity-based differences:

Conventional Oil: Petroleum found in liquid form (with gravity of greater than 20^o API) flowing naturally or capable of being pumped without further processing or dilution.

Unconventional Oil: Heavy Oil, Very Heavy Oil, Oil Shale, and Oil Sands are all currently considered unconventional oil resources. These compounds have a high viscosity and flow very slowly (if at all) and require processing or dilution to be produced through a wellbore. Heavy and Very Heavy Oil are liquid resources, while Oil Shale and Oil Sands are solids that can be processed into synthetic crude oil.

> **Heavy Oil:** Heavy crude oils are understood to include only those liquid or semi-liquid hydrocarbons with a gravity of 20^o API or less. The fuel oils remaining after the lighter oils have been distilled off during the refining process.
>
> **Very Heavy Oil:** On the production side, Very Heavy Oil is defined as having a gravity less than 10^o to 12^o API.
>
> **Oil Shale:** A fine-grained sedimentary rock containing *kerogen*, a solid organic material. The kerogen in oil shale can be converted to oil through the chemical process of pyrolysis. During pyrolysis, the oil shale is heated to 445^o-500^o C in the absence of air and the kerogen is converted to oil and separated out, a process called "retorting." Whether extracted by surface mining or underground in-situ processes, the material must be extensively processed to yield a marketable product (synthetic crude oil). "Oil shale" is unrelated to liquid petroleum in fractured shales that is sometimes called "shale oil."
>
>> *Kerogen*: A complex mixture of compounds with large molecules containing mainly hydrogen and carbon but also oxygen, nitrogen, and sulfur. Kerogen is a precursor of petroleum and the organic component of oil shales. It is waxy, insoluble in water, and upon heating, it breaks down into recoverable gaseous and liquid substances resembling petroleum.

Oil Sands: Also referred to as Tar Sands or Bituminous Sands, Oil Sands are a combination of sand, water, and *bitumen*.

> *Bitumen* is a semisolid, degraded form of oil that will not flow unless heated or diluted with lighter hydrocarbons. Bitumen is converted into synthetic crude oil or refined directly into petroleum products by specialized refineries.

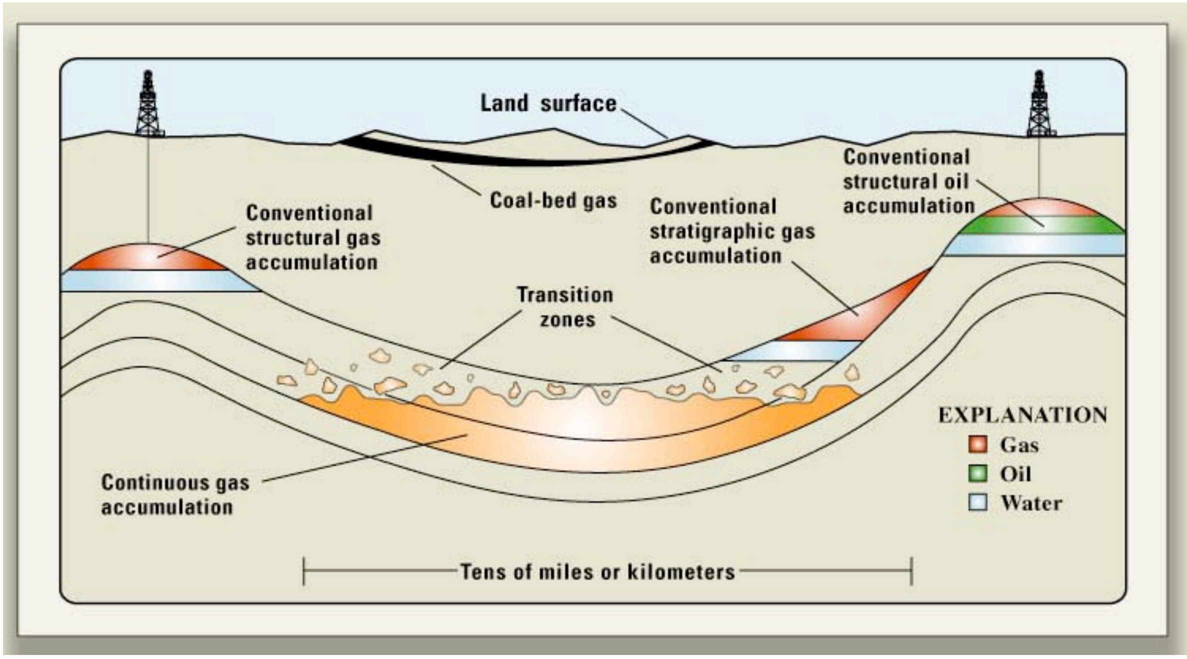
Although the difference between conventional versus unconventional accumulations is often viewed to be a matter of oil viscosity, this one variable cannot be used to fully capture the difficulties which attend estimating hydrocarbon resources.

In this light, some organizations, such as the USGS, use the term 'continuous resources' to define those resources that are economically produced but are not found in conventional reservoirs (see Figure 8). Conventional accumulations are described in terms of discrete fields or pools localized in structural or stratigraphic traps by the buoyancy of oil or gas in water. Conventional accumulations have a *trap and seal* which prevent the petroleum from escaping; they are confined to a *reservoir* horizon with defined thickness and lateral continuity; and they are limited down-dip by a horizontal contact zone with underlying water. This geologic setting means that the geometries, and therefore volumes, of each accumulation can be inferred with some precision.

Continuous accumulations are petroleum accumulations (oil or gas) that have large spatial dimensions and indistinctly defined boundaries, and which exist more or less independently of the water column. Continuous accumulations have two key geologic characteristics: (1) they consist of large volumes of rock pervasively charged with oil or gas, and (2) they do not appear to depend upon the buoyancy of oil or gas in water for their existence. Because they may cover hundreds, or even thousands, of square miles, they may occur across a wide range of stratigraphic environments, each of which may have widely varying reservoir properties. Or they may exist in their *source rock,* never having *migrated* into a *carrier bed* or *reservoir.* This all means that it is very difficult to obtain even a properly framed stochastic view of how big or small these resources might be because it is not always clear how big an individual "accumulation" might be.

Conventional accumulations "float," bubble-like, on water; continuous accumulations do not. Continuous accumulations have two key geologic characteristics: (1) they consist of large volumes of rock pervasively charged with oil or gas, and (2) they do not appear to depend upon the buoyancy of oil or gas in water for their existence.

Figure 8. Graphical representation of conventional and continuous petroleum accumulations (Schenk and Pollastro, 2002).



1.3 Previous Estimates – Results, Methodology, Differences, and Challenges

Many different organizations conduct resource estimates, for a variety of different purposes. Figure 9 shows a plot of global oil and gas endowment estimates that have been reported plotted against the date of the assessment. These estimates are plotted on the basis of oil equivalent, meaning that the gas resource estimates have been converted to an energy equivalent volume of oil for comparison. Note that prior to 1958, most estimates were totaled less than 2 trillion barrels of oil (TBO). Since 1958, not only have the estimates grown, but the variability of the estimates has increased. Variations in resource estimates are caused by a variety of factors, which are discussed in more detail below.

Figure 9. Comparison of world oil and natural gas resource endowment estimates (Ahlbrandt *et al.*, 2005).

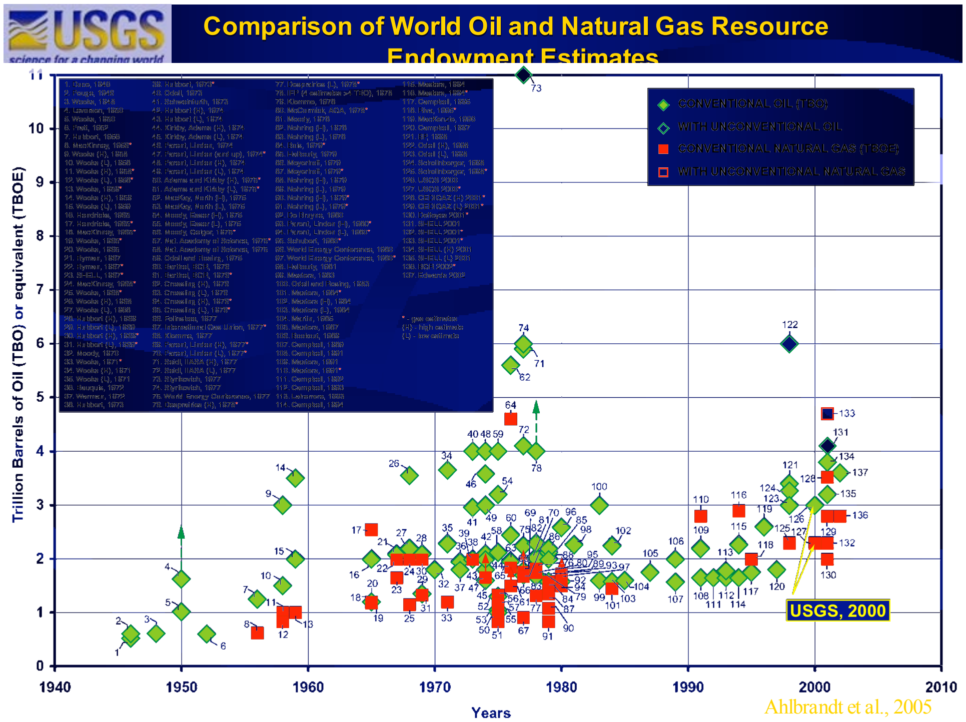
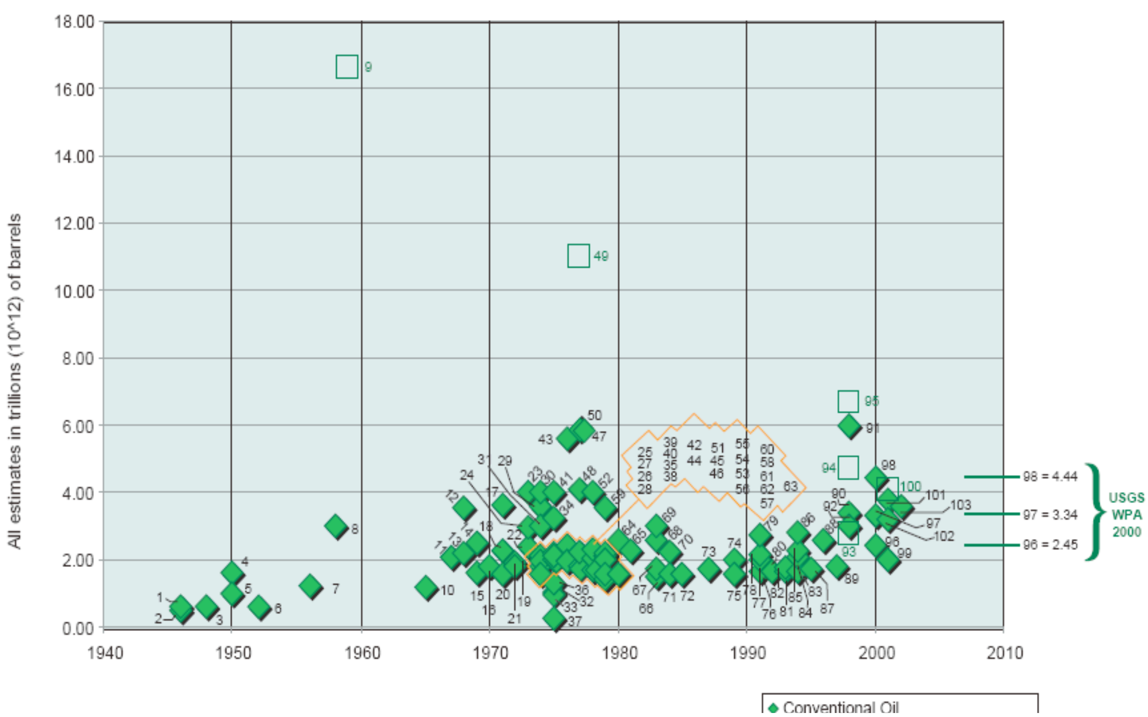


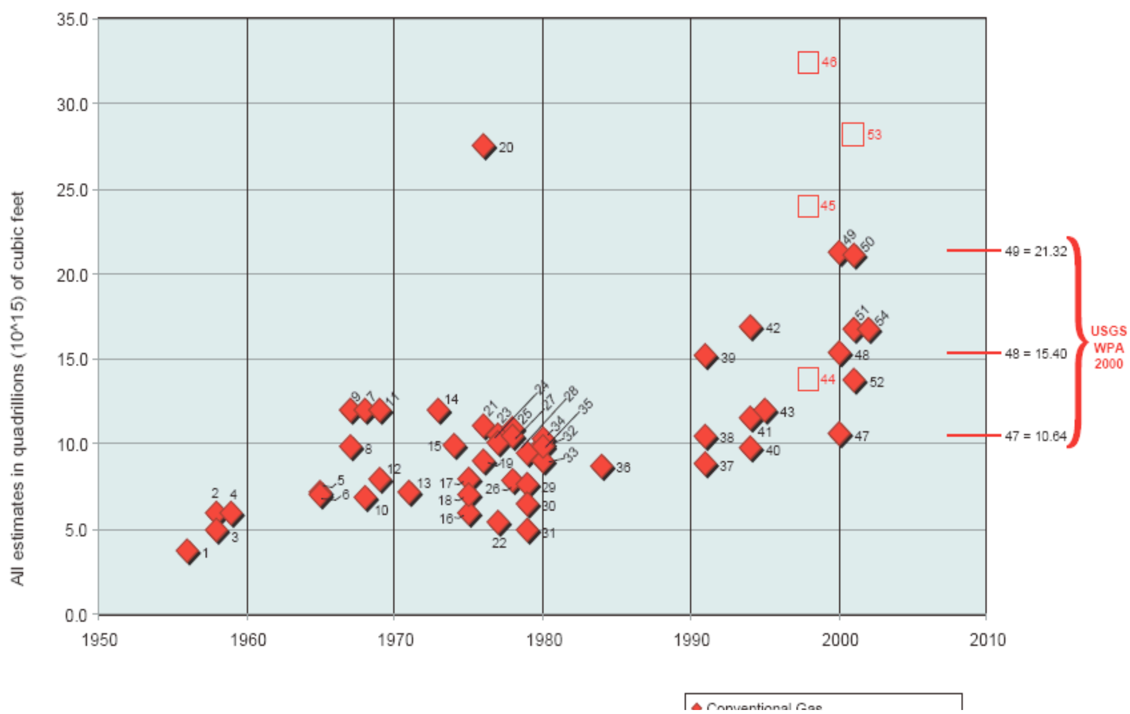
Figure 9a. World oil resource estimates from Figure 9, above.



Conventional Oil / Conventional + Unconventional Oil
References

1	Duce	38	Moody, Geiger	75	Campbell
2	Pogue	39	Moody, Geiger	76	Campbell
3	Weeks	40	National Academy of Science	77	Masters
4	Levorsen	41	Odell and Rosing	78	Masters
5	Weeks	42	Barthel, BGR	79	Masters
6	Pratt	43	Grossling	80	Campbell
7	Hubbert	44	Grossling	81	Campbell
8	Weeks	45	Folinsbee	82	Laherrere
9	Weeks	46	Klemme	83	Campbell
10	Weeks	47	Seidl, IIASA	84	Masters
11	Ryman	48	Seidl, IIASA	85	Masters
12	Weeks	49	Styrikovich	86	Masters
13	Weeks	50	Styrikovich	87	Campbell
14	Hubbert	51	World Energy Conference	88	MacKenzie
15	Hubbert	52	IFP (4 estimates >4 TBO)	89	Campbell
16	Moody	53	Klemme	90	BP
17	Weeks	54	Moody	91	Odell
18	Weeks	55	Nehring	92	Odell
19	Bauquis	56	Nehring	93	Schollnberger
20	Warman	57	Halbouty	94	Schollnberger
21	Warman	58	Halbouty	95	Schollnberger
22	Hubbert	59	Halbouty	96	USGS
23	Odell	60	Meyerhoff	97	USGS
24	Schweinfurth	61	Nehring	98	USGS
25	Hubbert	62	Nehring	99	Deffeyes
26	Hubbert	63	De Bruyne	100	SHELL
27	Kirkby, Adams	64	World Energy Conference	101	SHELL
28	Kirkby, Adams	65	Halbouty	102	SHELL
29	Parent, Linden	66	Masters	103	Edwards
30	Parent, Linden	67	Masters		
31	Parent, Linden	68	Masters		
32	MacKay, North	69	Odell and Rosing		
33	MacKay, North	70	Masters		
34	Moody, Esser	71	Masters		
35	Moody, Esser	72	Martin		
36	Moody, Esser	73	Masters		
37	Moody, Geiger	74	Bookout		

Figure 9b. World gas resource estimates from Figure 9, above.



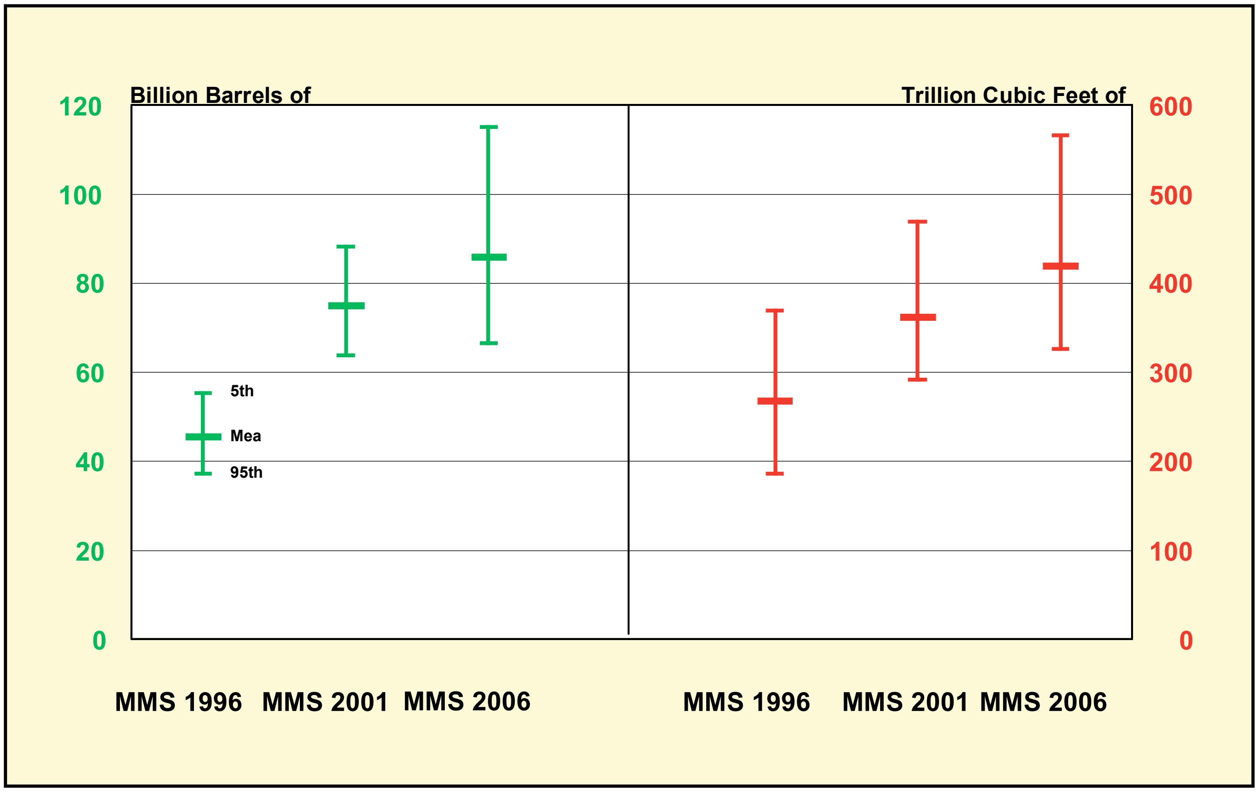
Conventional Gas / Conventional + Unconventional Gas
References

1	MacKinney	38	Masters
2	Weeks	39	Masters
3	Weeks	40	Masters
4	Weeks	41	Masters
5	MacKinney	42	Masters
6	Weeks	43	Riva
7	Ryman	44	Schollnberger
8	SHELL	45	Schollnberger
9	MacKinney	46	Schollnberger
10	Weeks	47	USGS
11	Hubbert	48	USGS
12	Hubbert	49	USGS
13	Weeks	50	CEDIGAZ
14	Hubbert	51	CEDIGAZ
15	Parent, Linden	52	SHELL
16	Adams and Kirkby (H)	53	SHELL
17	Moody, Geiger	54	BGR
18	National Academy of Science		
19	Barthel, BGR		
20	Grossling		
21	Grossling		
22	International Gas Union		
23	Parent, Linden		
24	Parent, Linden		
25	Desprairies		
26	Desprairies		
27	McCormick, AGA		
28	Bois		
29	Meyerhoff		
30	Nehring		
31	Nehring		
32	Parent, Linden		
33	Parent, Linden		
34	Schubert		
35	World Energy Conference		
36	Masters		
37	Masters		

Remember that resource estimates are snapshots in time; they represent only what has been assessed – an amalgamation of those parts of the world (what basins, what plays, what regions or countries, etc.) and those commodities (oil, natural gas, conventional, unconventional) taken into consideration and supported by what data are available at the time of the assessment. Assessing additional types of resources or additional parts of the world can greatly change an assessment. For example, the USGS World Petroleum Assessment 2000 included areas that were judged to be significant on a world scale in terms of known petroleum volumes, geologic potential for new petroleum discoveries, and political or societal importance. Subsequent assessments by the USGS include areas that were not included in the 2000 overview and the USGS is currently conducting an assessment of the entire circum-Arctic. Also note that in Figures 9a and 9b, those estimates that include unconventional resources are (not surprisingly) greater than those resource estimates that do not.

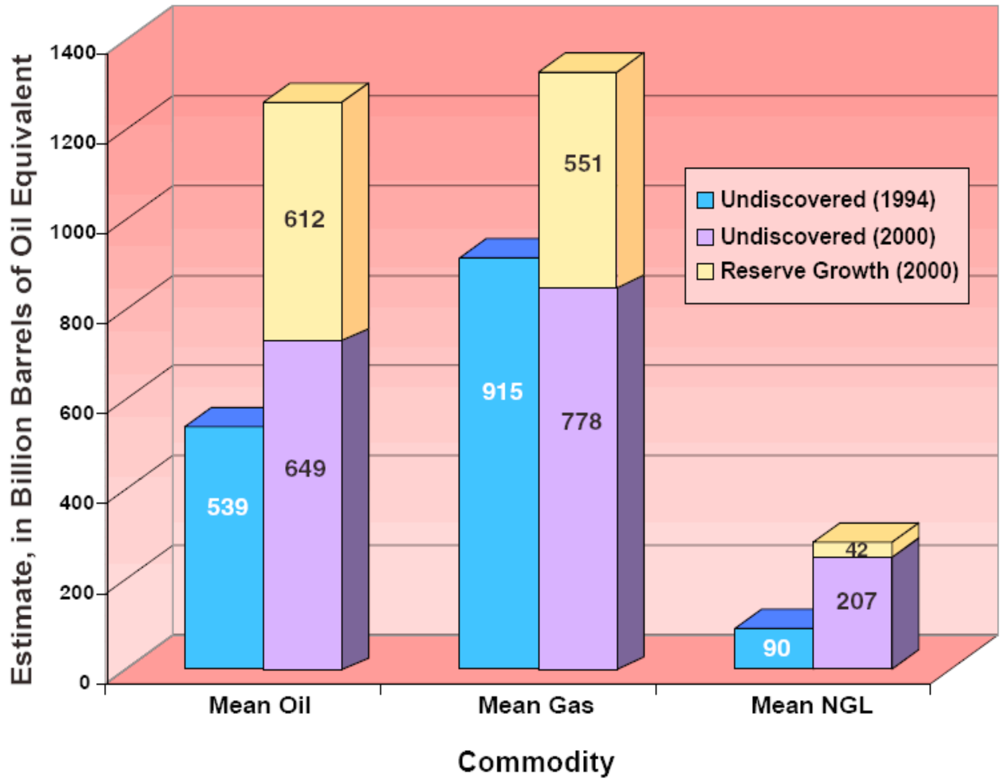
Since the earth has a finite endowment of liquid hydrocarbons, from which we produce more and more each year, the logical conclusion would be that the estimates for what remains to be found should be going down, but this is not the case. Usually, resource estimates conducted by an individual organization tend to increase over time. One example of this is the Minerals Management Service (MMS) assessment of the U.S. Outer Continental Shelf (Figure 10).

Figure 10. Comparison of MMS assessments of the U.S. Outer Continental Shelf over time (http://www.mms.gov/revaldiv/PDFs/2006NationalAssessmentBrochure.pdf).



USGS estimates, like those of other organizations, change over time as well. Compared to previous USGS world petroleum assessments (Masters and others, 1994, 1997), undiscovered volumes from the 2000 assessment (exclusive of the U.S.) were 20% greater for oil, and 130% greater for NGL (Figure 11), largely because reserve growth was quantitatively assessed and factored into this assessment for the first time. Other reasons that assessments grow over time include technological advances increasing the amount and type of resource available for development and increased geologic understanding of the resource.

Figure 11. Graph comparing the 1994 and 2000 USGS world estimates, exclusive of the United States for undiscovered conventional oil, gas, and NGL, in billion barrels of oil equivalent. (From USGS, 2000)



To understand and illustrate the robustness of the estimates outlined in Figure 10 and examine the significant differences that exist among the published estimates, two tables of the characteristics of the resource estimates were compiled, one table for selected oil estimates (Table 3) and one estimate for selected gas estimates (Table 4). These tables attempt to summarize some of the factors relevant to interpretation and understanding of those estimates, where those factors are documented. Only those estimates for which information was included with the resource estimates are included in the tables.

1.31 Differences in Assessment Methodology

This section explains some of the differences in methods used to estimate undiscovered potential, many of which need to be considered in designing a 'best practice' method for estimating future reserves and resources.

There are two fundamentally different mathematical approaches to assessing undiscovered volumetric potential:

Deterministic Methods – estimates made by an individual, or group of individuals (the Delphi approach), in which a 'best guess' estimate is made of undiscovered potential. In such estimates, the range of possible outcomes is not captured, and (often) the rationale behind the estimate is not well documented. Prior to 1980, most estimates of global endowment took this form.

Probabilistic (Stochastic) Methods – produce a range of possible recoverable volumes associated with their estimated likelihood; recoverable volumes are demarked by standardized confidence levels, or probabilities. Stochastic methods can be of varying types, but all accept that the number of fields in a basin or play, and the volume of hydrocarbons they contain, are finite and can be characterized by a distribution. Differences arise from disagreements about the shape of the distribution which should be used, how and whether the distribution should be truncated, whether it is continuous or multimodal, and how much (if any) of the distribution has already been fully sampled.

In addition, the fundamental differences between unconventional and conventional (or continuous) accumulations require that different methods be used to estimate undiscovered volumetric potential. As mentioned earlier, the assessment of conventional resources focuses on the number of remaining undrilled prospects (discrete potential structural or stratigraphic traps, often a number in the tens, or possibly hundreds) and expected future field size characteristics. For continuous resource assessments, the basic unit of assessment becomes the number of wells that will ultimately be needed to develop the entire play area (often a number in the thousands), and the expected recovery per well. The USGS has published several hallmark papers on this topic that may be found at http://energy.cr.usgs.gov/oilgas/noga/methodology.html.

During the last 30 years, the methodology for assessment of undiscovered conventional oil land gas resources used by the USGS has undergone considerable change (Charpentier and Klett, 2005). The change is based on five major principles: (1) a need for a methodology suitable for immaturely explored as well as maturely explored areas, (2) use of as comprehensive a set of geological and exploration history data as possible, (3) use of geological analysis and not solely statistical methods, (4) transparent and reviewed methodology and robust documentation, and (5) an increased utility of the assessment results and documentation for multiple purposes.

In general, the variances between estimates are due to one or more of the following differences or limitations:

1) Many estimates reported reserves and did not factor in reserves growth. This lack results in a pessimistic outlook for reserves and a pessimistic forward estimate for future size characteristics (and therefore, undiscovered oil resources);

2) Some estimates were only made for selected basins of the world and are therefore not totally inclusive.

3) Some estimates include only crude oil. Others include other petroleum liquids such as condensates – liquids extracted during production from gas fields. This can be a large volume, especially in areas of large gas fields or gas potential.

4) Many of the estimates, particularly the early estimates, are deterministic; that is, they are based upon a single-point estimate of inputs and provide a single-point estimate for the estimated volumes. As such they fail to capture, and express, the possible range of possible volume outcomes.

5) “Most likely” numbers are reported in some cases. “Most likely” is a term which has varying meaning to different assessors. In some cases this number reflects the average value from the assessment (generally a value occurring or exceeded about 30% of the time), sometimes the median value is reported (the value that will be exceeded exactly 50% of the time), and sometimes the modal, or most likely value is reported (which is exceeded 80% or 90% of the time). This prevents comparison of values, since the overall ranges are often not reported.

6) Some estimates reflect only the application of current technology, while others try to anticipate future advances in exploration and completion technology.

7) Variations in minimum estimated field size. The volume of resource is concentrated in relatively large fields. Differences in the minimum field size assessed will also make estimates less comparable.

8) Differences in methodologies for assessing endowment. The methodology chosen to make an assessment can have a major effect on the estimate (Ahlbrandt and Klett, 2005). The choice of methodology is, in itself, a major subjective factor in performing an assessment.

9) Differences in technologic and economic assumptions. All estimators make technologic and economic assumptions, but not all estimators state their assumptions explicitly. Some estimators assume contemporary levels of technology and contemporary economics. Others assume varying increases in technologic progress and increases in prices and/or consider volumes that are available under different economic conditions (e.g. at $40/barrel oil vs. $60/barrel oil).

10) Differences in temporal perspective. Some assessors try to answer the question of what will actually be discovered within a particular time frame. Other assessors try to assess some part of the geologic state of nature regardless of future exploration (for example, an estimate of numbers of fields larger than a certain minimum).

11) Differences in geologic interpretation. Some estimates are based on geologic interpretation. Assessors must consider different geologic hypotheses and evaluate the probabilities of each. The irreducible geologic uncertainty makes this comparison of multiple working hypotheses inescapably subjective.

Many of these differences are understandable and acceptable, but must be kept in mind when trying to compare the many different estimates in the public and private domain.

1.4 The way forward – Needs for best practice estimates of remaining hydrocarbon volumes

Considering all that has been stated above, there is a great need for resource assessments to have extensive documentation and groups conducting assessments to be consistent with what they produce and have a standardized, transparent methodology for themselves. Estimates cannot be compared unless one knows what was or was not included in those estimates. Another important need is for estimates to be detailed: a single estimate at the world scale is of limited usefulness. Estimates at country, geologic province, or play level have the potential to be relevant to a far greater number of questions and can be more easily understood and refined.

A future, state-of-the-art assessment of remaining hydrocarbon endowment must incorporate all of the following characteristics:

- Clear definition as to what constitutes 'conventional vs. unconventional'

- Probabilistic methodology to capture uncertainty (understanding that many previously available estimates are deterministic, and therefore global aggregations will contain both probabilistic and deterministic elements)

- Systematic, global assessments, including oil- and gas-in-place estimates, where appropriate

- Play based approach, from which basin/country/continent rollups can be accomplished

- Consistent economic perspective to assessments

- Industry cooperation, including national oil companies

- Documentation for every input that goes into the analysis

1.5 Study Observations

Global endowment is not a limiting factor in future supply in the near term (constraints will come from other sources – technology, access (remote/frontier areas), deliverability, economics/markets, geopolitical considerations)

There are a great many differences in resource assessments, but there are sometimes good reasons for those differences (different purposes).

There is a great deal of uncertainty in resource estimates, by their very nature – uncertainty is an inherent part of resource estimation.

World reserve growth is poorly known but probably very large (on the same scale as undiscovered conventional).

Global Reserve Growth multiplier(s) elusive

Small changes in recovery efficiency (percentage of oil in place that will ultimately be produced) will have a globally strategic impact upon the global oil budget.

The role of unconventional resources upon the global energy budget will have a growing and profound impact.

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Column explanations:

Author - Author(s) of original reference
Year - Publication year of original reference
Estimate 1 – The value of the low estimate given in the reference. Values are in trillion barrels or quadrillion cubic feet
Estimate 1 type –
- Low – a low estimate without a particular probability value attached
- F90 – a low estimate with 90% probability of greater than this value
- F95– a low estimate with 95% probability of greater than this value

Estimate 2 – The value of the intermediate estimate given in the reference. Values are in trillion barrels or quadrillion cubic feet
Estimate 2 type –
- Point estimate – a single-valued non-probabilistic estimate
- Mode – the estimate with the highest probability density of the probability distribution
- Most likely– the estimate with the highest probability density of the probability distribution
- Mean – an estimate that is the statistical average over the entire probability distribution
- Expected value – an estimate that is the statistical average over the entire probability distribution

Estimate 3 – The value of the high estimate given in the reference. Values are in trillion barrels or quadrillion cubic feet
Estimate 3 type –
- High – a high estimate without a particular probability value attached
- F10 – a high estimate with 10% probability of greater than this value
- F05– a high estimate with 5% probability of greater than this value
- Maximum – a high estimate with 0% probability of greater than this value

Area assessed – Was the assessment for the total world or just selected areas
Scale of original assessment – World, basin, or play
What was actually assessed? – What part of the resource base was actually assessed versus what part was merely quoted from other sources
Methodology
- Areal yields – use of analog ratios of volumes of resource per geographic area
- Basin analysis– geologic analysis at the basin scale
- Comparison of previous estimates – subjective averaging of previous estimates
- Discovery extrapolation – use of discovery-history trends
- Field-size distribution extrapolation– use of field-size distribution assumptions

Multiple – use of several methods
Play analysis – geologic analysis at the play scale
Production extrapolation– use of production-history trends
Volumetric yields– use of analog ratios of volumes of resource per volume of sedimentary rock

Methodology documentation – None, minimal, intermediate, extensive