UK ENERGY RESEARCH CENTRE

UKERC Review of Evidence on Global Oil Depletion

Technical Report 3:

The Nature and Importance of Reserve Growth

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Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function.

The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is useful to policymakers.

This report forms part of the TPA's assessment of evidence for **near-term physical constraints on global oil supply**. The subject of this assessment was chosen after consultation with energy sector stakeholders and upon the recommendation of the TPA Advisory Group, which is comprised of independent experts from government, academia and the private sector. The assessment addresses the following question:

What evidence is there to support the proposition that the global supply of 'conventional oil' will be constrained by physical depletion before 2030?

The results of the project are summarised in a *Main Report*, supported by the following *Technical Reports*:

1. Data sources and issues
2. Definition and interpretation of reserve estimates
3. Nature and importance of reserve growth
4. Decline rates and depletion rates
5. Methods for estimating ultimately recoverable resources
6. Methods for forecasting future oil supply
7. Comparison of global supply forecasts

The assessment was led by the Sussex Energy Group (SEG) at the University of Sussex, with contributions from the Centre for Energy Policy and Technology at Imperial College, the Energy and Resources Group at the University of California (Berkeley) and a number of independent consultants. The assessment was overseen by a panel of experts and is very wide ranging, reviewing more than 500 studies and reports from around the world.

Technical Report 3: The nature and importance of reserve growth examines the reasons why estimates of the size of oil fields tend to grow over time and the extent to which this may be expected to continue in the future. It looks at the causes of this phenomenon, the relative importance of these different causes, the methods available for forecasting future reserve growth and the validity of the assumptions used about reserve growth in an authoritative study of global oil resources. It concludes that reserve growth is of crucial importance for future global oil supply and is not primarily the result of conservative reporting.

Contents

Figures

Tables

Executive Summary

The term reserve growth refers to the increase in the estimates of ultimately recoverable resources (URR) of known fields over time. Reserve growth has contributed significantly more to reserve additions than new discoveries over the past decade and is expected to continue to do so in the future. But despite the crucial importance of reserve growth for future global oil supply, it remains both controversial and poorly understood.

There is a great deal of work to be done before reliable estimates of future reserve growth can be made. This entails both the collation of adequate and reliable field-level data from which to extrapolate future reserve growth, and updating and refining the very rough and preliminary forecast made by the US Geological Survey (USGS), which remains the most comprehensive study to date.

'Unpacking' the definition of reserve growth down to its constituent elements reveals that there are a number of definitional issues still to be resolved, in particular regarding the definition of reserves themselves and what categories of oil should be included. For the purposes of estimating reserve growth, it must be clearly defined what categories of oil are considered as their growth characteristics may be different.

The data on which estimates of reserve growth are currently made is both thin and frequently unreliable: Adequate field-level data is only publicly available for a small number of regions around the world (notably the US) and the observed reserve growth in these regions may not be representative of that in other regions. Global field-level data is only available from a small number of sources and these rely upon reserve estimates that are frequently not subject to third-party auditing. Owing to its expense, this data is inaccessible to most analysts, although regional data is available at more moderate cost. The latter allow reserve growth to be estimate at the regional level, but the same is not possible using public domain sources such as the BP Statistical Review.

Geological, technological and definitional factors all contribute to reserve growth: Improvements in geological knowledge result in an increase in the volume of oil known to exist. Technological factors may increase the amount of oil that it is possible to extract but do not change the known below-ground conditions. Definitional factors change neither the amount in place nor the amount extracted, and therefore definitional confusion and changes should be avoided at all cost.

The relative contribution of different factors to reserve growth remains uncertain owing to both insufficient study and inadequate data. It may also be expected to vary between regions and over time. But significant reserve growth is observed in cumulative discovery estimates based upon 2P reserves in many regions of the world. Also, numerous studies document the importance of technological and geological factors in contributing to reserve growth. These sources may therefore be expected to make a major contribution to future global oil supply.

The rate of reserve growth appears to vary widely between different types of fields and could change significantly in the future: Reserve growth appears to be greater for larger, older and onshore fields, so as global production shifts towards newer, smaller

and offshore fields the rate of reserve growth may decrease in both percentage and absolute terms. At the same time, higher oil prices may stimulate the more widespread use of EOR techniques that have the potential to substantially increase global reserves. The suitability of such techniques for different sizes and types of field and the rate at which they may be applied remain key areas of uncertainty.

The USGS reserve growth forecast is the best available preliminary study. However, the authors of the report themselves state that the USGS forecast is not meant to be anything other than a rough estimate using inadequate data and some sweeping assumptions. On the evidence of reserve growth data since its publication, the USGS forecast appears to be performing well. This does not validate the assumptions but it does give some confidence in at least the short-term future predictions.

Although every effort is made by the USGS authors to assess uncertainty of the results, the final statement in terms of F5 and F95 fractiles is not only inconsistent with reserve definition standards, but also meaningless when results are quoted in other publications unless the assumed triangular probability distribution is also specified. This report recommends the calculation of a mean (equivalent by the assumptions in the report to the F50) and standard deviation from the given figures. This is a considerably more intuitive presentation and, being simpler, more likely to be retained when results are quoted out of context.

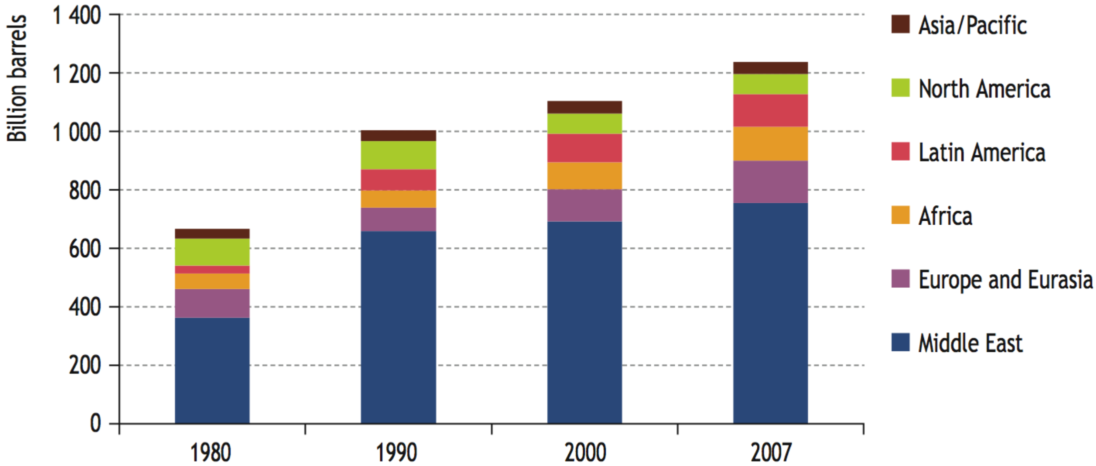
If longer-term forecasts are to be made, better data will be required. The methodology of the USGS appears to be sound, but the data on which it is based are not reliable. If better data were available, specifically field-level 2P or mean estimate data for a world-wide sample of major producing countries, it would be possible to estimate reserve-growth functions more accurately and thus improve regional as well as global reserve growth estimates.

1 Introduction

Despite continually rising production, and declining discovery since 1964, world proved oil reserves are at their highest ever level (Figure 1.1) and are forecast to continue to rise at least in the short term (IEA, 2008). This is largely a result of the phenomenon of so-called reserve growth, which is defined as "the commonly observed increase in recoverable resources in previously discovered fields through time" (Klett and Schmoker, 2003). Reserve growth is perhaps a misleading term, since what is observed to grow is not the declared reserves of those field, but the estimates of the ultimately recoverable resources (URR) from those fields (Arrington, 1960). This represents the sum of declared reserves at a particular point in time and the cumulative production up to that time. Reserve growth leads to an increase in the estimates of URR for an oil-producing region, without any new fields being discovered.

While the magnitude and rate of reserve growth is of critical importance for future global oil production, the topic remains both highly controversial and poorly understood. The aim of this report is to summarise the current state of observation and modelling of reserve growth and to highlight some relevant implications.

Figure 1.1: Global proved oil reserves, 1980-2007.



Source: IEA (2008), Figure 9.3.

Reserve growth may result from a number of factors including initial underestimation of oil in place, discovery of related oil-bearing formations at the same site, improvements in production technology or revisions to publicly declared estimates of recoverable reserves. The relative importance of these different factors may be expected to vary from one field to another and over time.

To examine the nature and magnitude of reserve growth, it is necessary to obtain time series data on the production and reserves of individual fields. Unfortunate, this data is only available in the public domain for a limited number of regions around the world - notably the US, the UK and Norway. Most other countries restrict access to field-level data in full or in part. Moreover, even for those countries where data are available, there are definitional issues regarding what can be counted as reserve growth. Historical data on reserve growth (where available) can be used to predict future reserve growth but the experience in one region may not necessarily provide a good guide to reserve growth in another region. Forecasting future reserve growth is important, however, since it is anticipated to make a major contribution to future global oil production.

The structure of the report is as follows. Section 2 defines reserve growth and examines the factors that contribute to it, while Section 3 looks at the availability and reliability of data relevant to estimating reserve growth. Section 4 examines the development of 'growth functions' for forecasting future reserve growth and investigates how reserve growth varies between different sizes and types of fields. Section 5 takes a closer look at the methodology used by the US Geological Survey (USGS) for forecasting reserve growth at the global level and compares the observed reserve growth since 1995 with the USGS forecasts. Section 7 concludes.

2 Nature and source of reserves growth

2.1 Defining reserve growth

Reserve growth is defined by the US Geological Survey (USGS) as:

> "The increases in known (recoverable) petroleum volume that commonly occur as oil and gas fields are developed and produced. The terms reserve growth and field growth are used interchangeably."

The 'known recoverable petroleum volume' is defined as:

> "The sum of cumulative production and remaining resources - sometimes called ultimately recoverable resources, or URR."

'Known' is a rather misleading term, since we do not actually 'know' that this total recoverable volume exists until it has all been extracted; it would better be termed 'estimated'. To reflect this, the sum of cumulative production and the remaining recoverable resources is sometimes referred to as *cumulative discoveries*. This represents an *estimate* of the ultimately recoverable resources (URR) at a particular point in time. The actual URR of the field will only be known when production has ceased. *Reserve growth therefore refers to the increase in the estimated URR of known fields over time*.

Cumulative production is generally known fairly accurately, but remaining resources must be estimated and hence will depend upon the particular geological, technical and economic assumptions that are used (IEA, 2008). As described in Thompson *et al.* (2009), the estimate of remaining resources will vary according to the level of confidence that is assumed, with a distinction commonly being made between: proved (1P) reserves; proved and probable (2P) reserves; and proved, probable and possible (3P) reserves. Estimates of remaining resources – and hence cumulative discoveries - may be based upon any of these definitions, with the less certain estimates being larger.

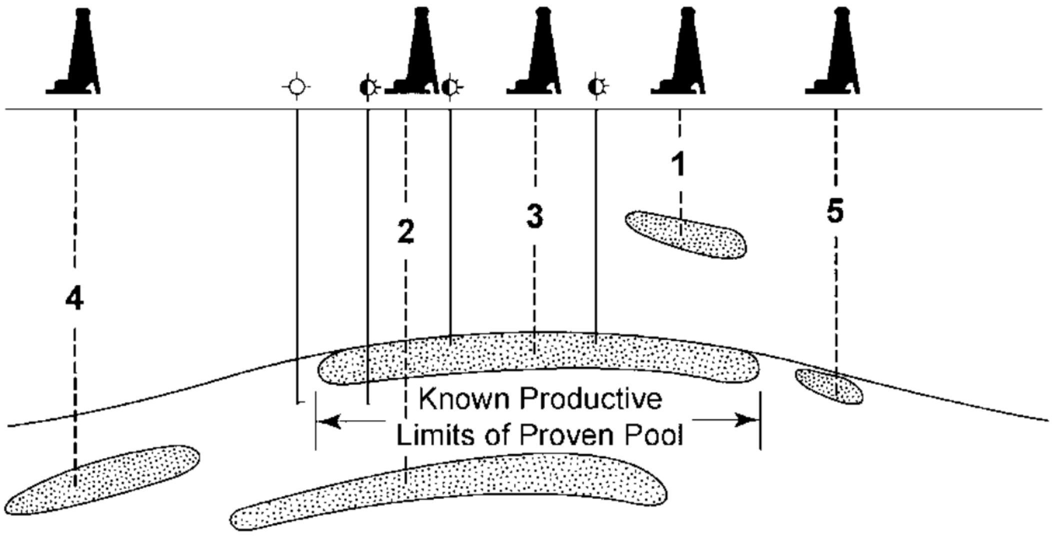
Recoverable" means that the oil is both technically feasible and economically viable to extract. Estimates of recoverable reserves are therefore dependent on assumptions about technology and economics (IEA, 2008; SPE, 2007). For example, it may not be physically possible to extract oil from reservoirs found under deep water until drilling technology for that depth of water becomes available. Alternatively, there may be a large technically recoverable reserve, but due to the high costs of extraction it may only be economically recoverable when the oil price exceeds a certain threshold (which will depend upon the structure, location and characteristics of the field).

The multiple factors that contribute to reserve growth can be grouped under three headings, namely *geological*, *technological* and *definitional* (Klett and Verma, 2004b). The relative contribution of each of these factors will necessarily depend on the characteristics of the field in question; for example, geologically well-characterised fields are unlikely to yield new reserves by further exploration but are more likely to be suitable for application of new technology. Definitional factors are likely to be more important in nations where the operating environment is less stable.

2.2 Geological factors

Geological factors represent an increase in the estimates of *original oil in place* (OOIP) for a reservoir, field or region as a result of improved geological knowledge. For example, new (perhaps deeper) reservoirs or extensions to previous reservoirs may be discovered or a better understanding of the volume, shape and characteristics of reservoirs may be obtained through the use of seismic and other techniques. There may be inconsistent classification in some circumstances, depending in part on the order in which the reservoirs are discovered (Attanasi and Coburn, 2004). In some cases, smaller fields that were previously classified as separate may be merged into larger fields as exploration proceeds (Figure 2.1). Inconsistencies such as these can greatly complicate the analysis and interpretation of the relevant time-series data.

Figure 2.1: Illustration of the difficulty of judging what represents a single field.



Note: Disconnected regions may be classified either within the same field (contributing to reserve growth), or as new discoveries (not reserve growth), depending on the definitions used and the order of drilling.
Source: Attanasi and Coburn (2004).

2.3 Technological factors

Technological factors represent those activities which increase the estimated recovery factor, or the proportion of the OOIP that is both technically possible and economically viable to recover. This can result from better characterisation of reservoirs and optimised drilling as well as from the application of improved recovery technologies. Recovery factors can be as high as 80% for high permeability reservoirs, though the estimated global average is around 34% (IEA, 2008).[1]

It is common to distinguish between *primary recovery* where oil is recovered under its own pressure; and *secondary recovery* where active pumping or water/gas injection is employed to increase reservoir pressures and the flow of oil to the surface. Some fields, notably offshore ones where production costs are higher, may begin production with secondary recovery. After this, *enhanced oil recovery* (EOR) techniques may sometimes be employed to boost production (Box 2.1). These include: injection of

[1] The recovery factor is the ratio of the estimated URR to the estimated OOIP. Estimates of regional and global average recovery factors should be treated with considerable caution (IEA, 2005). For example, Laherrère (2006) uses IHS data to estimate a global average recovery factor of only 27%.

supercritical carbon dioxide (CO_2), thermal heating of the reservoir to reduce hydrocarbon viscosity, injection of polymers or foams which have a greater viscosity and thus improve displacement efficiency, use of microbes which produce surfactants to improve flow, and advanced well designs to increase contact between the injected fluid and oil. The suitability of these techniques varies with the type, accessibility and characteristics of the reservoir. Subsurface injection of CO_2 is one of the most widely used techniques, but has previously been limited by the lack of natural sources of CO_2. However, this method could gain more widespread use in the future with the CO_2 being obtained from carbon capture and storage (CCS) technology,

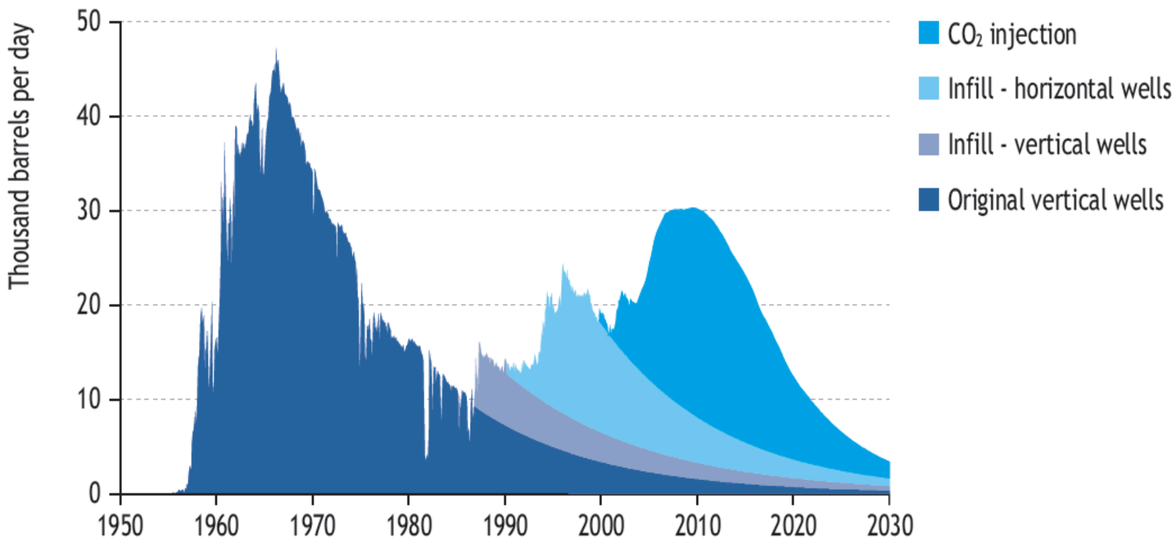
Extensive use of EOR in the US has led to recovery factors that are ~5% higher than the global average and there is considerable scope for the application of these technologies in other regions of the world. In principle, each percentage increase in the global average recovery factor could add some 80 Gb to global reserves, equivalent to nearly three years of current production. The IEA (2008) estimates that the global average recovery factor could be raised as high as 50%; however, this could take 'much more than two decades' to achieve.

Box 2.1.Enhanced oil recovery techniques

There are three broad groups of EOR techniques:

- *Thermal* methods introduce heat, typically in the form of steam to reduce viscosity, partially 'crack' heavy oil and/or increase pressure. They are particularly suitable for heavy oil but their use has declined since the mid-1980s.
- *Gaseous* methods inject carbon dioxide, nitrogen or other gases at high pressure to reduce viscosity, achieve 'miscibility' (a homogeneous solution), displace water, sustain pressure and mobilise a larger proportion of the oil. CO_2 injection is the fastest growing form of EOR and is very effective for light oil. While many applications use natural sources of CO_2, future projects may be linked to carbon capture and storage (CCS) technologies.
- *Chemical* methods inject various compounds to reduce the 'interfacial tension' between oil and injected water. These are not widely used and tend to be complicated, unpredictable, costly and sensitive to reservoir characteristics.

The IEA (2008) use the example of the Weyburn field in Canada (see below) to illustrate what can be achieved with EOR – in this case with additional vertical and horizontal drilling followed by CO_2 injection. But it is not clear how widely this example can be reproduced.



Source: IEA (2008); NPC (2007); Sandrea and Sandrea (2007).

2.4 Definitional factors

Definitional factors comprise a mix of definitional, legal, economic and political influences which influence reserve estimates but are independent of either the OOIP or our technical capability to extract it. The publicly declared reserve estimates on which the analysis of reserve growth is generally based may be very different from the estimates used internally within a company:

> "…..Ask a manager in an oil company what the reserves are and he or she will tell you that it depends on who is asking. The manager will also tell you that three sets of books are kept - one that has the optimistic estimates that are used to sell deals to upper management and the stockholders and to give the geologists are good measure for what they have found; another has the conservative estimates that the accountants used to borrow money from the banks; and a third set has the middling numbers calculated by the engineers for internal use in the company." (Drew, 1997)

Of particular importance are changes in reserve classification schemes, such as occurred in Russia in the 1990s and are currently underway in the US. This includes the practice of excluding reserves at discovered fields that have yet to receive production sanction. There may also be an implicit shift in definitions over time as a result of changes in personnel, operators and reporting cultures. Since all reserve definitions require assessment of economic viability, changes in technology, oil prices and other economic conditions may also affect the volume of declared reserves.

A good example of a definitional change is Royal Dutch Shell's decision to downgrade their declared proved reserves in 2004. This is not a decision the company would have taken lightly, as it caused an immediate fall in the share price and the subsequent resignation of various senior executives. Such a large revision serves to highlight the uncertainty in reserves figures as well as their extreme sensitivity.

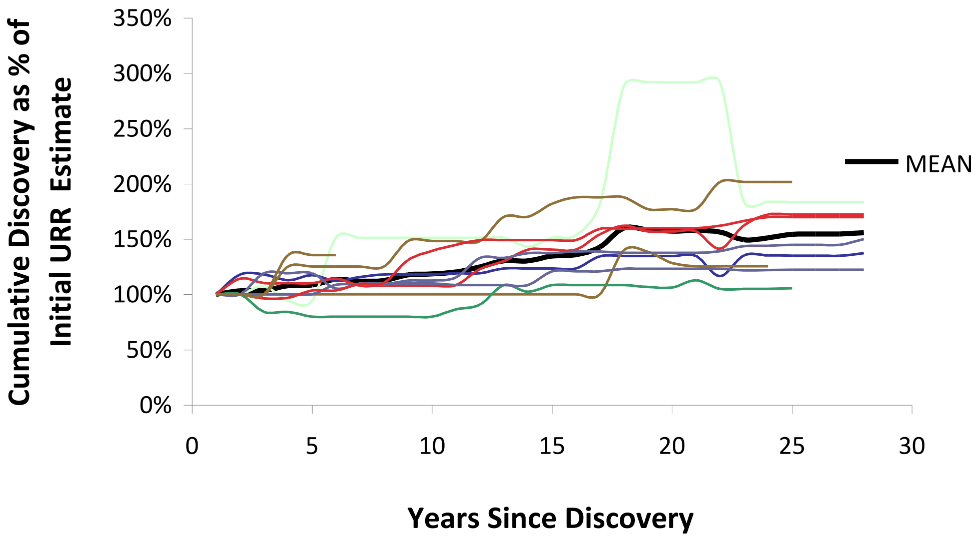
The amount of reserve growth should depend upon the particular definition of reserves on which the cumulative discovery estimates are based (e.g. 1P or 2P). Reserve growth may be particularly high for cumulative discovery estimates based upon 1P reserves since these are highly conservative estimates that typically underestimate the remaining recoverable resources. For example, under the probabilistic interpretation of 1P reserves, there should be a 90% probability of the recoverable resources exceeding the 1P figure (Thompson, *et al.*, 2009).[2] Hence, as production proceeds and 1P reserve estimates are revised, we would expect cumulative 1P discoveries to increase. This will appear as reserve growth in the publicly declared figures, but may have nothing to do with either changes in geological knowledge or improvements in technology (Bentley, *et al.*, 2007)

In contrast, reserve growth should be smaller for cumulative discovery estimates based upon 2P reserves since, under the probabilistic interpretation, there should only be a 50% probability of the recoverable resources exceeding the 2P figure.[3] Hence, we would expect cumulative 2P discovery estimates to be downgraded as frequently as they are upgraded. However, analysis suggests that this is generally not the case. With respect to 1P, 2P and 3P reserve estimates Drew (1997) notes that: "…the irony …….is that all three sets of numbers are pessimistic – they all grow with the passage of time" (Drew, 1997).

As an illustration, Figure 2.2 shows the change in cumulative discovery estimates for large fields in the UK Continental Shelf (UKCS). These estimates were published by the UK government and we take them to be based upon 2P reserves. For these fields, the mean estimate of cumulative discoveries increased by approximately 50% over 27 years, while none of the estimates decreased in size. However, smaller fields in the UKCS grew by only 20% over this period while many fields discovered since 1980 have shown a reserve decrease (Figure 2.3).

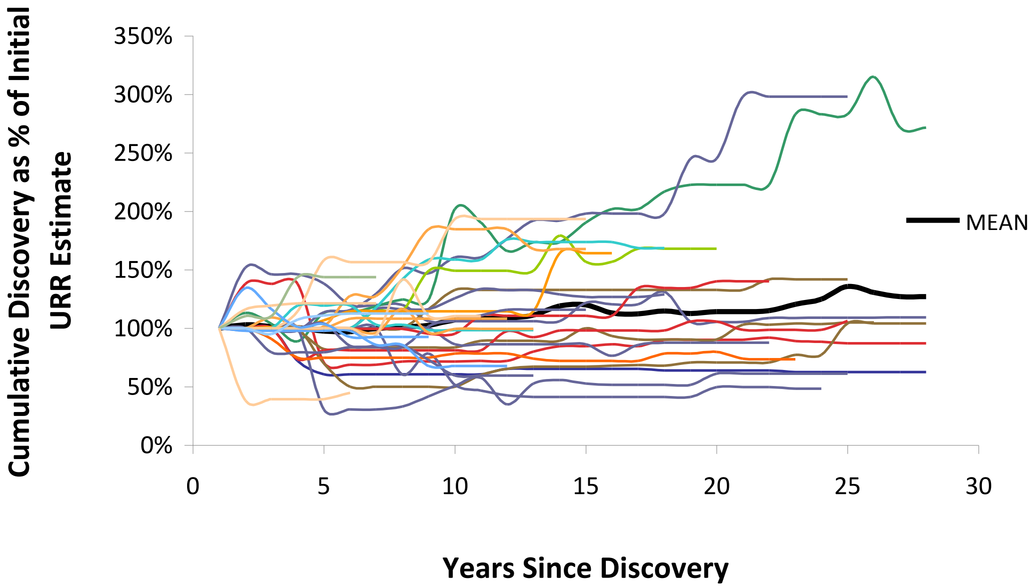
[2] Furthermore, the inappropriate aggregation of 1P reserve estimates may make regional and global estimates more conservative still (Pike, 2006; Thompson, *et al.*, 2009).
[3] Also, the aggregation of 2P estimates is much less likely to lead to bias (Pike, 2006; Thompson, *et al.*, 2009).

Figure 2.2: Reserve growth in oil fields larger than 0.5 Gb in the UKCS



Source: BERR (ex-DTI)
Note: Horizontal axis represents years after first production. Vertical axis is cumulative discoveries for each field, expressed as a percentage of the initial declared reserves. Heavy black lines are the simple arithmetic means of percentages, un-weighted by volume. This data series is no longer published by BERR, in part because of inconsistencies in reporting between different operators.

Figure 2.3: Reserve growth in oil fields smaller than 0.5 Gb in the UKCS



Source: BERR (ex-DTI)
Note: Horizontal axis represents years after first production. Vertical axis is cumulative discoveries for each field, expressed as a percentage of the initial declared reserves. Heavy black lines are the simple arithmetic means of percentages, unweighted by volume. This data series is no longer published by BERR, in part because of inconsistencies in reporting between different operators.

3 Data for the study of reserve growth

To model reserve growth accurately, it is necessary to obtain successive yearly estimates of the reserves and production of individual fields. Since the changes in size of individual fields are extremely variable, it is necessary to use a statistically significant sample of fields from a relatively homogeneous population. Unfortunately, such data is only available for a limited number of regions around the world.

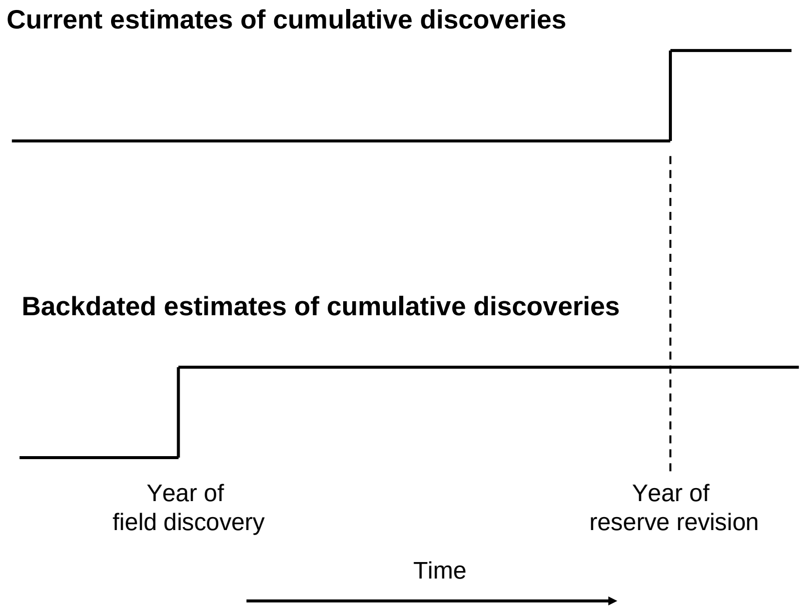
The US Energy Information Administration (EIA) has collected data on US fields since 1977. The Oil and Gas Field Integrated Field File contains annual estimates of 1P reserves, annual production and cumulative production for all the oil and gas fields in the US. In addition, the Minerals Management Service (MMS) maintains a comprehensive database of offshore fields in the Gulf of Mexico, while Nehring Associates maintain a database of 16000 'Significant' Oil and Gas Fields of the United States (i.e. fields with an estimated URR > 0.5 mboe). All of these use 1P reserve data, reported under rules established by the Securities and Exchange Commission (SEC). The UK Department for Energy and Climate Change and the Norwegian Petroleum Directorate maintain comparable databases for offshore fields in their countries, but these include estimates of 2P reserves. Since the reserve estimates that underlie these data sources are subject to verification by third parties, they should be reliable.

Globally comprehensive databases on individual fields are only available from a limited number of sources and these are both extremely expensive to obtain and subject to strict confidentiality requirements. In addition, since most of the reserve estimates that underlie these sources are *not* subject to third-party verification, they are necessarily less reliable. Both IHS Energy and Wood McKenzie maintain global databases of 2P reserves at the field level and the former is available under contract. A comparable database is maintained by Energyfiles in the UK, but its coverage is not as extensive as that of IHS and the data is not available to purchase. All these databases are updated each year, but for the detailed analysis of reserve growth it is necessary to obtain *annual* editions of these databases over a number of years. The general opinion appears to be that IHS Energy have the most complete and up-to-date dataset (Bentley, *et al.*, 2007). This company is the primary source of the data used by the US Geological Survey (USGS) to produce their estimates of future reserve growth at the global level (see Section 5) and their data is also used by the IEA for their annual World Energy Outlook.

Reserve growth can also be analysed using regional or country-level data, but only if reserve additions through new discoveries can be separated from the growth of existing fields. Unfortunately, the country-level data available from public domain sources such as the BP Statistical Review does not allow this distinction to be made. However, country-level data is also available from IHS Energy (for ~£4k/year, subject to confidentiality requirements) and this does allow reserve growth to be separately identified. The difference is that the public domain data sources record reserve revisions in the year in which they are made and make no adjustment to the data for earlier years. In contrast, IHS Energy *backdates* the revisions to the year in which the relevant fields were discovered. Figure 3.1 illustrates the corresponding effect on the time series of cumulative discoveries.

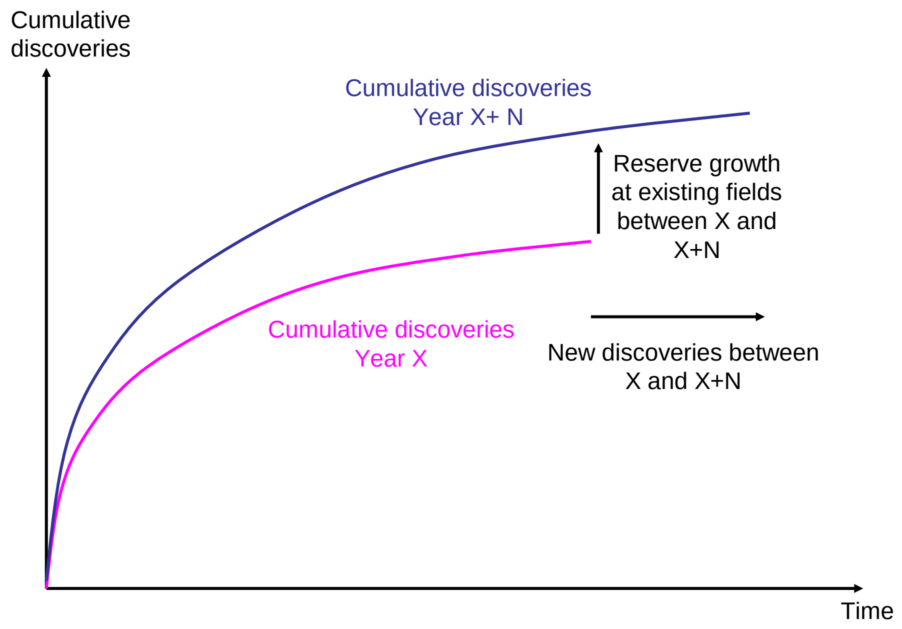
The logic of the 'BP approach' is that the reserves did not become 'available' for production until the estimate was revised and therefore should only appear at the time of the revision. The logic of the 'IHS approach' is that the reserves are contained in a field that was discovered many years earlier, so backdating provides a more accurate indication of what was 'actually' found at that time as well as what will ultimately be recovered from that field. Both of these approaches have their merits, although the difference between them is not always appreciated. But an additional advantage of the IHS approach is that it allows the aggregate reserve growth in a region to be estimated by comparing the backdated cumulative discovery estimates contained in the current edition of the database with those contained within earlier editions (Figure 3.2). This is not possible with public domain sources such as the BP Statistical Review.

Figure 3.1 Current versus backdated estimates of cumulative discoveries – treatment of reserve revisions



Note: With current estimates, reserve revisions increase the cumulative discovery estimates in the current year. With backdated estimates, these revisions are backdated to the year in which the relevant field was discovered and hence increase the cumulative discovery estimates for all intervening years. The treatment of newly discovered fields is the same in both cases.

Figure 3.2 Backdated estimates of cumulative discoveries – effect of reserve growth



A second key difference between the public domain data sources and the IHS Energy database is that former provide 1P reserve estimates while the latter provides 2P estimates. In principle, 2P reserves should be greater than 1P reserves, since they represent estimates of resources with a lower level of confidence. But at the global level, the BP estimate of 1P reserves is approximately the same as the IHS estimate of 2P reserves (IEA, 2008). This suggests that *either* that the 1P reserves are overestimated *or* that the 2P reserves are underestimated - or more likely a mixture of the two. While BP and others rely heavily upon data supplied by national governments, IHS Energy derives its information from a wider range of sources, with more attempts to verify its accuracy. Also, the discrepancies between the public and industry data sources vary widely from one region to another, being the largest for oil producers in the Middle East where in some cases the 1P estimates are actually greater than the 2P estimates (Bentley, *et al.*, 2007). Since these countries account for the bulk of the world reserves, they contribute to a corresponding uncertainty in the global estimates.

Estimates of regional and global reserve growth are therefore greatly constrained by the availability and accuracy of the required data. A detailed analysis of reserve growth requires access to time-series data on individual fields, but this is unlikely to be available to most analysts for most regions of the world. Estimates of reserve growth at the country and regional level may be derived from data supplied by IHS Energy, but this requires access to the databases from successive years, is subject to strict confidentiality requirements and provides no information on how reserve growth varies between different sizes, types and ages of field. Also, this data relates to geographical boundaries that do not correspond to geological boundaries, so the observed reserve growth will derive from a heterogeneous population of fields with different geological and operating characteristics. None of the above data sources are wholly reliable and the uncertainties are greatest where they matter most – namely, for those countries that hold the majority of the world's reserves.

4 Analysis and forecasting of reserve growth

4.1 Growth functions

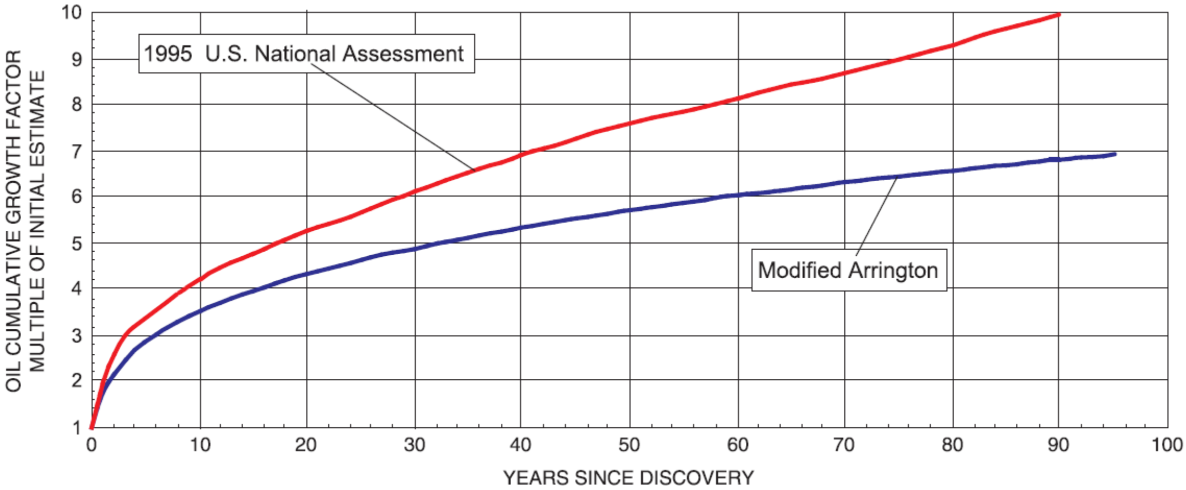
Reserve growth has been most closely studied in the United States, where it accounted for 89% of the additions to US proved reserves over the period 1978 to 1990 (Attanasi and Root, 1994).[4] While reserve growth also occurs in other regions of the world, the evidence base is much thinner since the data is poorer.[5] But despite being systematically investigated more than 40 years ago (Arrington, 1960), reserve growth was relatively neglected before the 1980s (Drew, 1997).[6] An important stimulus to further investigation was the retrospective examination of discovery forecasts for the US (Drew and Schuenemeyer, 1992). The forecasting methodology relied upon estimates of the size of known fields but failed to adjust these to allow for future reserve growth. Since these fields subsequently doubled in size within less than ten years, the volume of new discoveries was greatly underestimated. The USGS World Petroleum Assessment 2000 (USGS, 2000) was the first to systematically incorporate reserve growth into a global assessment of petroleum resources – a move which has generated considerable controversy (Laherrère, 2001).

Future reserve growth can be estimated through the creation of *reserve growth functions* based upon the measured growth of a statistically significant sample of fields (Root and Mast, 1993). Both annual and cumulative growth functions can be calculated and used to convert current estimates of cumulative discoveries into future estimates for a specified year, with the amount of growth depending solely upon the ‘age’ of the field. Field age serves as a measure of the development effort (e.g. infill drilling, improved recovery, pressure maintenance etc.) that contributes to reserve growth (Schmoker, *et al.*, 2000).

Figure 4.1 shows two growth functions estimated for onshore US oil fields (Attanasi and Root, 1994; Verma, 2005). Both show rapid growth in the years’ immediately following discovery and although growth subsequently slows, it is still continuing some 80 years later. Such findings are typical for US 1P data: for example, Lore, *et al.* (1996) found that the estimated size of offshore fields in the Gulf of Mexico doubled within six years of discovery and quadrupled within 40 years, while a later study by Attanasi (2000) suggested an eight-fold growth in 50 years.

[4] Relevant references include Verma (2003; 2005), Schmoker (2000), Nehring (1984), Attanasi and Root (1994), Root and Mast (1993), Schuenemeyer and Drew (1994) and Klett (2005).
[5] Relevant references include Klett (2005), Klett and Gautier (2005), Gautier and Klett (2005), Gautier, *et al* (2005), Klett and Schmoker (2003), Klett and Verma (2004a), Verma (2000; 2003; 2005), Verma and Ulmishek (2003), Verma, *et al.* (2004; 2001), Watkins (2002), Sem and Ellerman (1999) and Odell (1973)
[6] Exceptions in this intervening period included the work of Hubbert (1967), Arps, *et al.* (1970), Marsh (1971), Pelto (1973) and several Canadian studies (OGCB, 1970).

Figure 4.1 Cumulative reserve growth functions for US 1P data



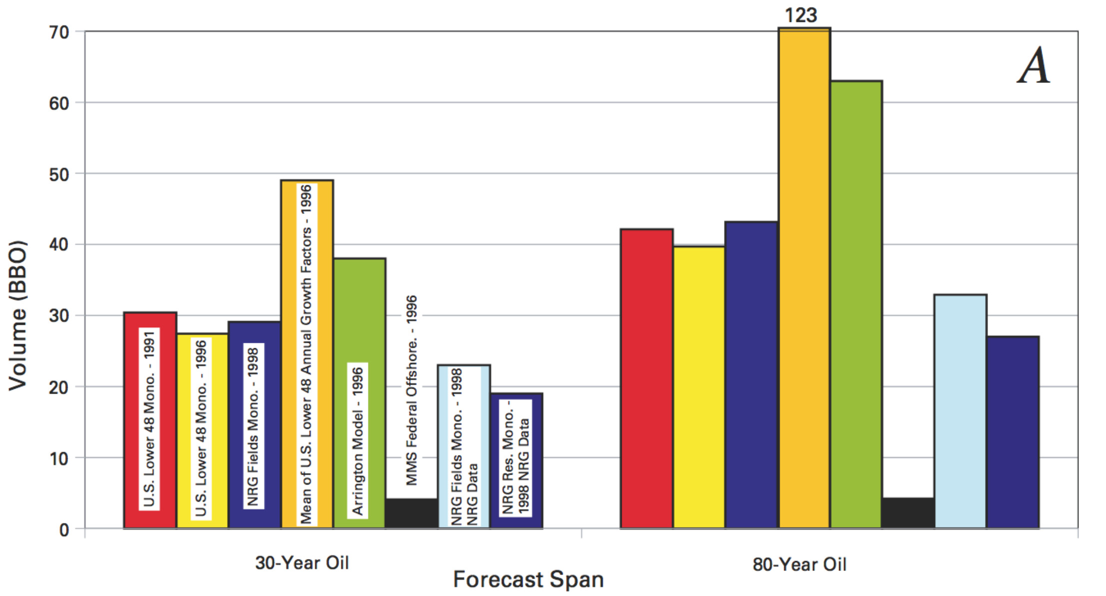
Source: Verma (2005)

While many US studies estimate growth functions from the date of field discovery (e.g. Attanasi, 2000), much of the development work that contributes to reserve growth occurs after production has commenced – which may be several years later (Klett, 2005). Hence, several authors estimate growth functions from the date of first production (Forbes and Zampelli, 2009; Sem and Ellerman, 1999; Watkins, 2002). Both approaches use age as the sole explanatory variable for reserve growth and hence neglect time-varying factors such as oil prices which could change the rate of growth by modifying the incentives for development drilling. The importance of economic factors was demonstrated by Forbes and Zampelli (2009) who found a strong positive correlation between gas prices and reserve growth the Gulf of Mexico, together with a negative correlation between operating costs (as measured by water depth) and reserve growth.

Figure 4.2 shows forecasts of future reserve growth for the US according to eight different reserve growth functions (Klett, 2003). The functions vary according to the dataset from which they are estimated and the method used. Each has been applied to a 1996 dataset from the EIA to estimate future reserve growth in the US over a 30 and 80 year period. The details of the calculations are technical but the spread in forecasts is significant. The MMS (Federal Offshore) forecast (in black) is considerably smaller than the others because it applies much smaller multipliers to older fields and assumes that fields older than 50 years will no longer experience reserve growth. The Arrington and Mean of Lower 48 forecasts are much larger because the dataset from which they were derived showed very significant reserve growth in both very old and very young fields.

This demonstrates that there is considerable disparity in US reserve growth functions, despite the use of comparable and overlapping data sets that all use the same (SEC) standard for reserve reporting. The variability in reserve growth for other regions of the world may be expected may to be correspondingly larger (although this will depend in part upon whether 1P or 2P reserve estimates are used). When combined with the comparative lack of data for these regions and the possibility that future growth patterns will depart from those experienced in the past, this creates enormous uncertainty in forecasting future reserve growth at the regional and global level.

Figure 4.2: Comparison of forecasts of future US reserve growth forecasts using different reserve growth functions.



Source: Klett (2003)

4.2 Variations in reserve growth between types and sizes of field

Reserve growth may be expected to vary between:

- different sizes of field (e.g. large fields may offer more opportunities for additional drilling and enhanced recovery technologies),
- different ages of field (e.g. the OOIP of more recently discovered fields may be estimated to a greater level of accuracy using modern seismic techniques);
- different types of field (e.g. opportunities for improved recovery may vary with the depth, temperature and pressure of the reservoirs and the density of the oil);
- different owners of fields (e.g. larger companies may have more money to invest than smaller companies); and
- different regions (e.g. reserve reporting standards may vary widely from one region to another, together with the economic incentives for expanding production).

Unfortunately, the lack of good-quality data on individual fields has prevented a systematic examination of such factors. However, some useful pointers can be obtained from the existing literature.

First, reserve growth varies widely between fields within the same region. For example, an analysis of 934 fields in the Gulf of Mexico found that approximately half grew over the period 1975 to 2002, one fifth shrank and the rest showed no significant change (Grace, 2007). Attansi and Root (1994) found that 'low quality' (notably heavy oil) fields grew five times more than conventional fields, while a study of 300 US fields showed that significant reserve growth was largely confined to fields with solution gas drive, heavy oils and low permeability in which techniques such as steam injection, hydraulic fracturing and CO_2 injection had been employed (Tennyson, 2002). This disparity makes the use of regional or global average growth functions problematic. Nevertheless, while the reserve growth for a particular field may be either positive or negative, the cumulative result for large groups of fields is invariably positive.

Second, reserve growth also varies significantly from one region to another, even when they are geologically similar. For example, studies show significantly greater reserve growth in Norwegian offshore fields than in either UK or Danish fields (Klett and Gautier, 2005; Sem and Ellerman, 1999; Watkins, 2002). Possible explanations for this include differences in field development practices, reserve definitions, reporting practices, treatment of NGLs and economic and regulatory conditions. Similarly, Verma and Ulmishek (2003) found that lack of investment contributed to West Siberian fields growing much slower than US fields of the same size.

Third, the source and extent of reserve growth varies over the life of a field. It seems likely that early stage reserve growth is more influenced by growth in the estimated OOIP while later stage growth is more influenced by changes in recovery factors (Beliveau and Baker, 2003). Growth is frequently very rapid immediately after field discovery reflecting continuing delineation of the reservoirs, but once production is well-established growth derives more from implementation of EOR, optimisation of well spacing and improved understanding of reservoir characteristics (Verma and Ulmishek, 2003).

Fourth, large fields grow more than small fields (see Figure 2.2 and Figure 2.3). For example, Verma and Ulmishek (2003) found that Siberian fields with a URR exceeding 1 Gb doubled in size in 19 years, while smaller fields increased by only 19% over the same period. The average for all fields was a 95% increase, since larger fields dominate total reserve additions. Similarly, Grace (2007) found that growing fields contained 80% of the discovered hydrocarbons in the Gulf of Mexico and were on average six times larger than fields that shrank. One possible explanation is that smaller fields are more completely explored before the confirmation of reserves, leaving less scope for growth in the estimated OOIP. But Grace also found that the dominant mechanism of reserve growth was the discovery of new reservoirs which is more likely to occur in large fields.[7] These results suggest that reserve growth may decline in the future (in both absolute and percentage terms) as the average size of new discoveries declines. However, other studies have found no statistically significant correlation between field size and reserve growth (Forbes and Zampelli, 2009; Klett and Gautier, 2005).[8]

Finally, some evidence suggests that onshore fields may grow by more than offshore fields (Watkins, 2002) and that older fields may grow by a greater proportion than more recent discoveries. For example, Forbes and Zampelli (2009) find a shift to a lower ‘reserve growth regime’ in the Gulf of Mexico after 1987, following the more widespread use of 3-D seismic techniques that allowed more accurate estimation of a field’s size. Again, these results suggest that reserve growth may decline in the future

[7] There were 78 single reservoir fields, of which 33 shrank in size, 27 were static and 18 grew.
[8] Forbes and Zampelli (2009) study the same region as Grace (2007), but focus on gas fields.

as a greater share of production derives from newer, smaller and better delineated fields that are more likely to be located offshore.

5 The USGS estimates of potential global reserve growth

5.1 The USGS World Petroleum Assessment

Most analysis of reserve growth has taken place in the US, where the SEC rules require the reporting of a particularly conservative interpretation of 1P reserves that is confined to oil that is in contact with a well. As a result, authors such as Laherrère (1999) argue that the primary source of observed reserve growth is conservative reporting.[9] In contrast, 'optimists' such as Mills (2008) highlight the historic and potential contribution of improved technology. This disagreement was brought to a head by the publication of the USGS World Petroleum Assessment (WPA) in 2000 which provided an authoritative global assessment of the ultimately recoverable resources of conventional oil (USGS, 2000).

The USGS study considered resources that had 'the potential to be added to reserves' between 1995 and 2025 using existing technology. This required assumptions about technical and economic viability and implies that the results could both *underestimate* the global URR (since some resources may only be technically and economically accessible in the longer term) and *overestimate* resource availability up to 2030 (since political and other constraints may prevent resources from being accessed and exploited). Also, since the study used a baseline of 1st January 1996, the estimates of cumulative discoveries were already five years out of date by the time it was published.

The most controversial aspects of the USGS 2000 study were the assumptions about future reserve growth (Laherrère, 2001). This had been excluded from previous global assessments by the USGS owing to insufficient data. However, this neglect was becoming increasingly inappropriate, given that reserve growth appeared to be accounting for an increasing proportion of global reserve additions. Using the Petroconsultants (later IHS) database, the USGS (2000) found that the cumulative 2P discoveries for 186 giant fields outside the US had increased by 26% between 1981 and 1996. This was greater than would have been predicted by the reserve growth functions estimated from US oil fields, despite the Petroconsultants database containing 2P reserves data while the US function was estimated from 1P data. Hence, the neglect of non-US reserve growth no longer seemed viable.

The 2000 study therefore included explicit allowance for future reserve growth for the first time. The USGS emphasized that their forecast of reserve growth was preliminary and that there were many approximations in the methods and a wide confidence band on the results. Nevertheless, the estimates they obtained have since been widely used within the oil industry and continued to underpin global supply forecasts by bodies such as the IEA (2008).

A summary of the full results of the USGS assessment are shown in Figure 5.1. This shows their mean estimates of the URR for crude oil, natural gas and NGLs, broken

[9] Reserve growth in the US may also be influenced by the production restrictions imposed in the 1950s and 60s ('pro-rationing') and by the underestimation of field size in the early days of exploration owing to inferior geophysical techniques.

down into the US and the rest of the world. Also shown are the quantities for which there is an estimated 5%, 50% and 95% chance of exceeding - indicating the range of uncertainty. For crude oil and NGLs combined, the mean estimate for reserve growth is 730 Gb (76 Gb in the US and 612 Gb in the rest of the world). This is 22% of the estimated global URR, 28% of the estimated remaining resources and exceeds the cumulative production of liquids through to 1995. Hence, the USGS anticipated reserve growth at existing fields to contribute almost as much to future reserve additions as new discoveries.

Critics were quick to argue that the global estimate of 730 Gb was wildly optimistic and the methods used by the USGS were flawed (Bentley, *et al.*, 2007; Laherrère, 2001). The principle difficulty lay in taking the US experience with reserve growth and extending it to fields elsewhere in the world. This is problematic for a number of reasons, but particularly because the US growth functions are based upon 1P reserve estimates while the global data used by the USGS is based upon 2P estimates. If the US reserve growth is primarily the result of conservative reporting (as many authors claim) the USGS approach will overestimate the global potential.

Figure 5.1: USGS estimates of the ultimately recoverable resource of conventional oil.

Table AR-1. World level summary of petroleum estimates for undiscovered conventional petroleum and reserve growth for oil, gas, and natural gas liquids (NGL).

[BBOE, billions of barrels of oil equivalent. Six thousand cubic feet of gas equals one barrel of oil equivalent. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Production and reserves normalized to 1/1/96. Shading indicates not applicable]

	Oil				Gas					NGL			
	Billion Barrels				Trillion Cubic Feet				BBOE	Billion Barrels			
	F95	F50	F5	Mean	F95	F50	F5	Mean	Mean	F95	F50	F5	Mean
World (excluding United States)													
Undiscovered conventional	334	607	1,107	649	2,299	4,333	8,174	4,669	778	95	189	378	207
Reserve growth (conventional)	192	612	1,031	612	1,049	3,305	5,543	3,305	551	13	42	71	42
Remaining reserves*				859				4,621	770				68
Cumulative production*				539				898	150				7
Total				2,659				13,493	2,249				324
United States													
Undiscovered conventional**	66		104	83	393		698	527	88	Combined with oil			
Reserve growth (conventional)**				76				355	59	Combined with oil			
Remaining reserves				32				172	29	Combined with oil			
Cumulative production				171				854	142	Combined with oil			
Total				362				1,908	318				
World Total (including United States)				3,021				15,401	2,567				

*World reserve and cumulative production data reflect only those parts of the world actually assessed and are from Petroconsultants (1996) and NRG Associates (1995).

**U.S. data from Gautier and others (1996) and Minerals Management Service (1996).

Source: USGS (2000).

5.2 The USGS method for estimating global reserve growth potential

The USGS procedure for estimating non-US reserve growth is summarised in Figure 5.2. The required inputs are global field data, a reserve growth function and a probability distribution.

The global data on field ages, cumulative production and 2P reserves were taken from the IHS database. The exception was Canada, where 1P reserves data was taken from

Nehring Associates. Fields were assigned to on of 270 'assessment units'[10] and checked to have reported discovery year before 1996 and a production status other than abandoned. The resulting dataset contained 13,618 fields (of which 8270 were oil fields) and represented approximately 95% of the discovered petroleum outside the US.

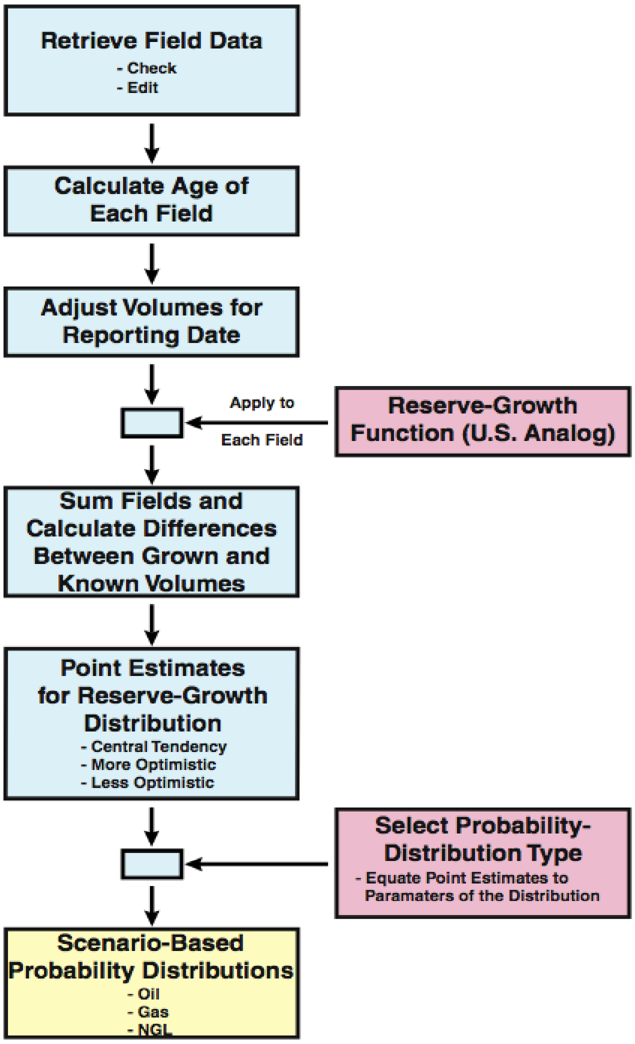
The reserve growth function was derived for fields in the US Lower 48 States and gave a multiplicative factor by which a field of a given age in that region would be expected to 'grow' in the course of the following 30 years. To calculate the expected global contribution of reserves growth over the timeframe, the same growth function was applied separately to every field in the dataset (oil, gas and NGL), subtracting the initial "ungrown" volume. The authors note that: "….Applying the same reserve-growth function to all fields implies that account was not made of regional and local variability of reporting systems, reserves definitions, and technical, economic and political conditions, all of which affect reserve growth". For different purposes, growth functions have been derived for various sub-regions of the United States, and the USGS suggested that a future improvement would be to select the most appropriate analog area for world regions with known geological characteristics.

To reflect uncertainty, the value calculated from the reserve growth functions was set equal to the mean of a probability distribution (Figure 5.3). In the absence of data with which to judge the correct shape, the distribution was chosen to be a triangle for ease of calculation. The minimum value was chosen to be zero, thereby rejecting the possibility of negative reserve growth. Having specified a minimum and a mean, the maximum value is then automatically defined.

Figure 5.4 shows the resulting cumulative probability distribution for total reserve growth for the rest of world (excluding US). The figures here match those in the second row of the table in Figure 5.1.

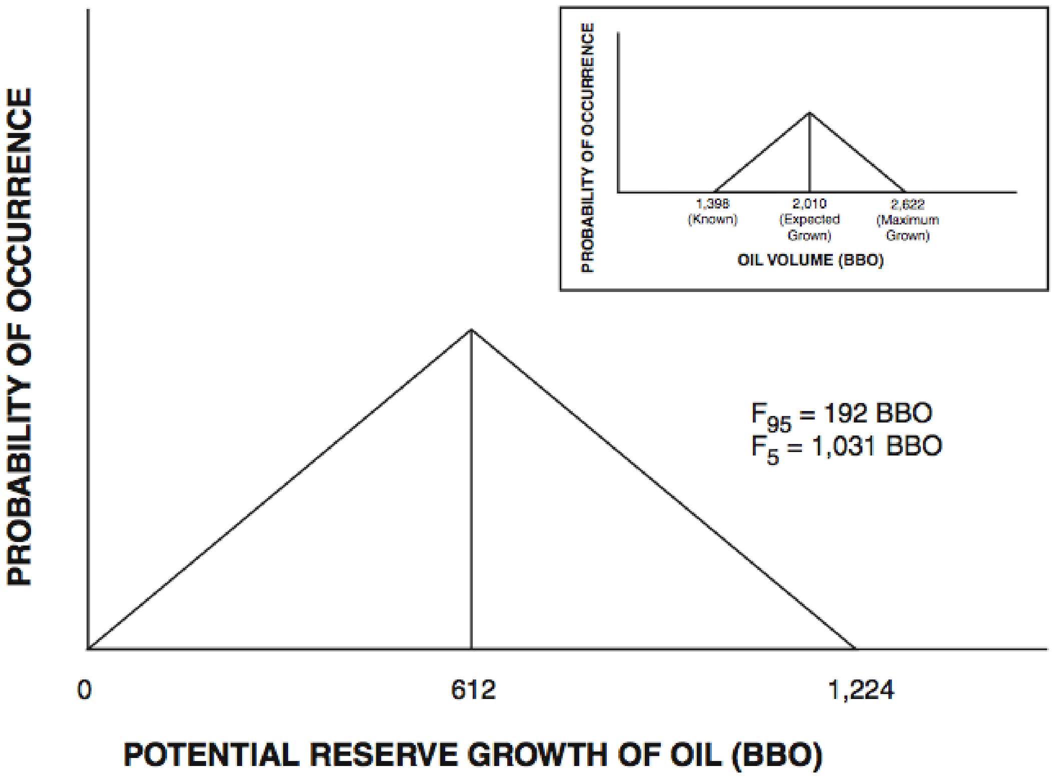
[10] An assessment unit (AU) is a volume of rock that is sufficiently homogeneous, both in terms of geology, exploration considerations, accessibility and risk to be examined with a particular resource assessment methodology.

Figure 5.2: USGS reserve growth evaluation methods,



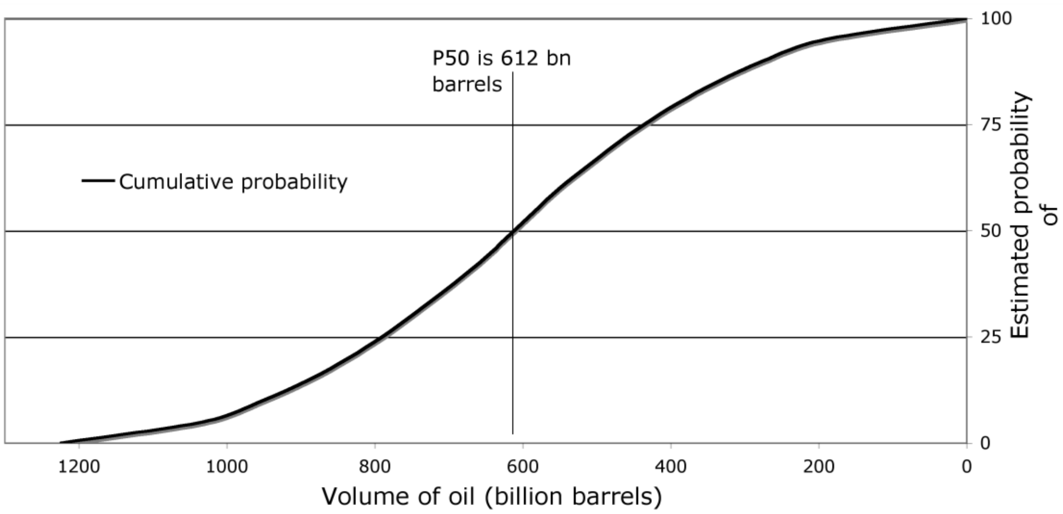
Source: USGS (2000), Figure RG-3

Figure 5.3: USGS reserve growth probability distribution for the rest of world (excluding US).



Source: USGS (2000)

Figure 5.4: USGS reserve growth forecasts (rest of world, excluding US) expressed as a probability distribution.



Note: The median value, or P50, of this distribution, is 612 billion barrels (and also the mean value, since it is symmetric).
Source: Calculated from data tabulated in USGS (2000).

5.3 Issues raised by the USGS method

The USGS highlight a number of factors that may lead their approach to *underestimate* future global reserve growth. For example:

- Longer timescales for development in the rest of world compared to US fields (either due to lack of incentives or less advanced technology) may mean that older fields continue to have more potential for reserve growth than those of similar age in the US;
- Improvements in recovery technology (especially EOR) may allow greater reserve growth than has been previously observed;
- A world petroleum shortage might incentivise greater investment in technology and therefore accelerate and enhance potential reserve growth;
- The aggregation of fields to produce global estimates is accurate only when adding the *mean* field size. In fact, the datasets used include both 1P (NRG Canadian oilfield data) and 2P reserves (rest of world). As discussed in Thompson *et al.* (2009), the most likely outcome is an underestimate of global reserves and hence of future reserve growth.

At the same time, a number of factors may lead their approach to *overestimate* future global reserve growth:

- The criteria specifying allowable technology for identification of reserves may in general be less restrictive in the rest of the world than in the US (i.e., the IHS data is based upon 2P reserve estimates while the US growth functions are based upon highly conservative 1P estimates). The result would be to increase known reserves and decrease future reserve growth potential;
- In some countries, reported reserves may be deliberately overstated (Bentley, *et al.*, 2007; Salameh, 2004);
- Fields in the rest of the world may tend to undergo greater field development prior to the publication of initial reserve estimates, making first estimates more accurate and reducing potential growth;
- A world economic recession and/or low oil prices may reduce industry investment in exploration and production, so that both discovery and potential growth of reserves are restricted;

The USGS argue that the margin of error is equally-spread either side of the 'best-guess' figure - i.e. the probability distribution should be symmetric (Figure 5.3). But other authors assign more or less importance to the above factors and come to different conclusions regarding the potential for bias. In most cases, the factors contributing to a potential overestimate of reserve growth are considered more important - and especially the difference between IHS 2P and US 1P reserve estimates.[11] However, some support for the use of US reserve growth functions was provided by an analysis of reserve growth at 186 non-US giant oilfields between 1981 and 1996. The 2P estimates of cumulative discoveries for these fields were found to have increased by 26% over this period, which was *greater* than would have been

[11] The USGS also acknowledge the drawbacks of using US reserve growth functions, but reject the alternative of using regionally specific reserve functions on the grounds of inadequate data. The alternative of ignoring reserve growth altogether could introduce even greater errors.

predicted by US reserve growth functions, despite the latter being based on 1P data (Klett and Schmoker, 2003).

The choice of a triangular probability distribution appears reasonable in the absence of additional data. However, the choice of zero as the minimum point rules out the possibility of negative reserve growth. This could be questionable for 2P data, since the latter implies a 50% chance of the reserves being greater or smaller than the initial estimate.

One difficulty with the USGS study is the presentation of results. Having calculated a probability distribution, the information regarding uncertainty is presented in the form of a table showing the 5% and 95% fractiles (Figure 5.1). Since these are rarely quoted alongside the mean values, the uncertainty information is generally lost when the results are used by other sources. It would be preferable to present the uncertainty in the form of a mean value plus-or-minus one standard deviation. For example, the probability distribution in Figure 5.4, results in a standard deviation of 250 billion barrels. Therefore, the rest of world potential reserve growth figure would be most usefully quoted as 612±250 billion barrels. This is more understandable to the non-expert than quoting the fractiles F5 and F95, especially when the shape of the probability distribution is not specified.

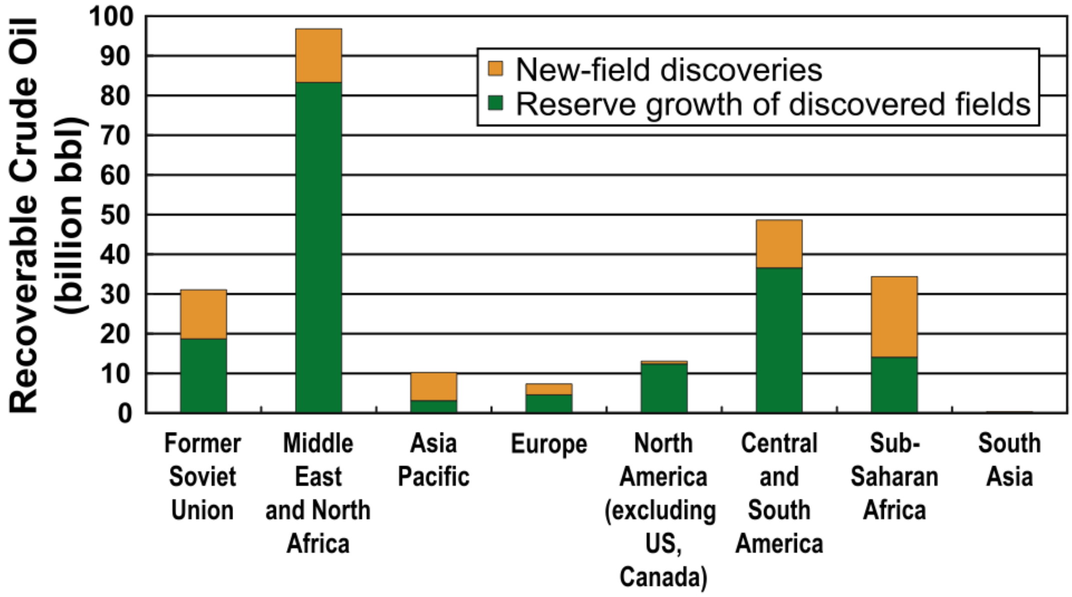
The choice of forecast timescale of 30 years appears a sensible balance between predicting enough of the future to be interesting and limiting the period of consideration to times which can reasonably expected to follow similar patterns to today. As the report concludes, *"[l]onger forecast spans for potential reserve growth would seem to be unjustfied, given that the economic and technical foundations of the petroleum industry are subject to significant change through time".*

5.4 Comparison with experience since 1995

Since we are now almost half way through the 1995-2025 time frame of the USGS study, it is possible to compare the estimates with actual experience. In an important study, Klett, *et al.* (2005) compared the forecast reserve growth with that observed in the IHS Energy database over the period 1995-2003. The analysis showed that during this period reserve growth added 171 Gb of oil to rest-of-world reserves (excluding US), or more than twice that added through new discoveries. The results suggest that 28% of the mean USGS estimate for non-US reserve growth had been added in the first 27% of the assessment time frame - an excellent agreement with the 'forecast'.

The same evaluation showed that reserve growth of gas fields was considerably ahead of the prediction (51% of the full estimate), while new discoveries were significantly behind (only 11% of the full estimate). Klett, *et al* suggest that these results may be explained by a preference for investment which enhances reserve growth over investment in exploration, as reserve growth represents a low-cost, minimal-risk strategy. This may imply that rates of reserve growth have been 'front-loaded' by investment and could diminish later in the forecast span. The authors also note that investment in various countries has been greatly constrained by political and economic factors, and that "…..in this context, it is surprising that as much as 11% of the estimated undiscovered oil resource was found, and that 28% of the estimated potential reserve growth was realized in the 8-yr period". Figure 5.5 shows the division by region of new field discoveries and reserve growth in the period considered, highlighting once again that reserve growth is a much larger contributor than new discoveries to reserve additions.

Figure 5.5: Additions to crude oil reserves as billion barrels from January 1996 to December 2003 by region.

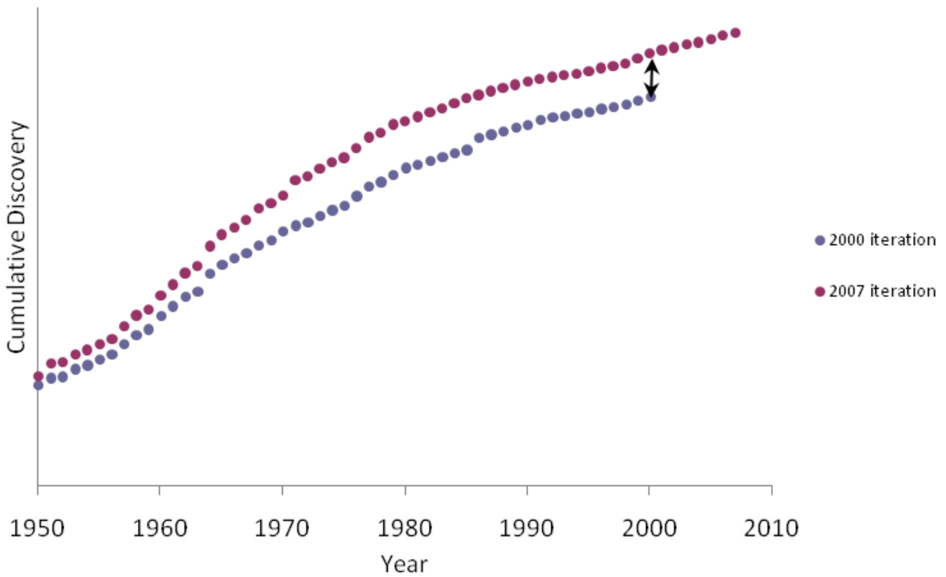


Source: Klett *et al.* (2005), Figure 2.

Bentley *et al.* (2007) question the Klett, *et al* evaluation, pointing out that definitional issues could contribute to the apparent increase in reserves. For example, Stark and Chew (2005) found a global total of 465 Gb of reserve growth between 1995 and 2003, but only 175 Gb of this was attributed to 'classic' reserve growth and the remainder to 'new and revised data'. This distinction suggests that much of the apparent reserve growth could derive from factors such the inclusion of previously omitted fields in the industry databases and from revised estimates of fields where the data was poor. The biggest growth in absolute terms derived from Middle East fields where the reserves data is particularly uncertain.

To check whether the rate of reserve growth observed by Klett *et al.* is being maintained, we compared the 2000 and 2007 iterations of the IHS Energy database (Figure 5.6). The results suggest that cumulative 2P discoveries for pre-2000 fields grew by 11% over this period. The global figure includes US and Canadian data which is not comparable with the rest of the database since it is based upon 1P reserves. If the US data is removed, pre-2000 fields are estimated to have grown by 13.9% between 2000 and 2007, suggesting that the rate of non-US reserve growth has *increased* in recent years. The percentage reserve growth varies widely from one country to another (Table 5.1) with the largest contribution in absolute terms deriving from Saudi Arabia and Iran (Figure 5.7).

Figure 5.6 Reserve growth in the IHS database between 2000 and 2007



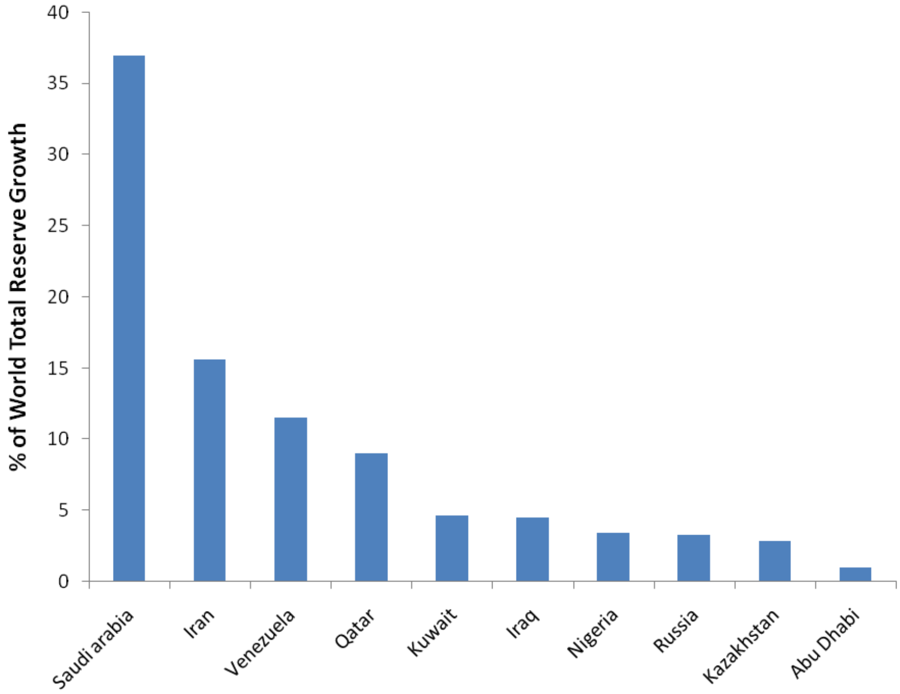
Source: IHS Energy
Note: Arrow indicates reserve growth for fields discovered before end 2000.

Table 5.1 Contribution of large producers to global reserve growth between 2000 and 2007

	Country	% growth 2000-2007	% global reserve growth
1	Saudi Arabia	27.5	37.0
2	Iran	23.5	15.6
3	Russia	3.0	3.3
4	Iraq	8.5	4.5
5	Venezuela	22.5	11.5
6	Kuwait	12.5	4.7
7	Abu Dhabi	3.2	1.0
8	Nigeria	15.8	3.5
9	Qatar	102.4	9.0
10	Kazakhstan	20.1	2.9

Source: IHS Energy

Figure 5.7 Contribution of large producers to global reserve growth between 2000 and 2007



Source: IHS Energy
Note: Percentage of global reserve growth for top ten oil-endowed countries ranked by remaining reserves.

In summary, though the actual rates may be contested, it is clear that significant reserve growth is observed in cumulative discovery estimates based upon both 1P and 2P reserves. With 2P data, the global average reserve growth observed since 1995 seems broadly in line with the assumptions made by the USGS (2000). Hence, the repeated assertions that the USGS study is discredited or overoptimistic seem at best to be premature. However, the global average reserve growth is strongly influenced by reserve growth in countries with the largest reserves where there is much less confidence in the accuracy of the data. Also, it is far from clear that the observed trend in reserve growth will be maintained in the future.

6 Conclusions

From this survey, the main conclusion is that there is a great deal of work still to be done in collating adequate data to forecast reserve growth and updating or refining the very rough and preliminary forecast made by the USGS.

- *Reserve growth, though itself well-defined, depends on other definitions:* 'Unpacking' the definition of reserve growth down to its constituent elements reveals that there are a number of definitional issues still to be resolved, in particular regarding the definition of reserves themselves and what categories of oil should be included. For the purposes of forecasting future global oil supply, it seems sensible to make the definition as broad as possible and include all possible contributions to oil reserves.
- *The data on which estimates are based is thin and frequently unreliable*: Reliable field-level data is only publicly available for a small number of regions around the world (notably the US) and the observed reserve growth in these regions may not be representative of that in other regions. Global field-level data is only available from a small number of sources and these rely upon reserve estimates that are not (able to be) subject to third-party auditing. Owing to its expense, this data is inaccessible to most analysts, although regional data is available at more moderate cost. The latter allow reserve growth to be estimate at the regional level, but the same is not possible using public domain sources such as the BP Statistical Review.
- *Geological, technological and definitional factors all contribute to reserve growth*: Improvements in geological knowledge result in an increase in the volume of oil known to exist. Technological factors may increase the amount of oil that it is possible to extract but do not change the known below-ground conditions. Definitional factors change neither the amount in place nor the amount extracted, and therefore definitional confusion and changes should be avoided at all cost.
- *Reserve growth is real, significant and not primarily the result of conservative reporting:* The relative contribution of different factors to reserve growth remains uncertain owing to both insufficient study and inadequate data. It may also be expected to vary between regions and over time. But significant reserve growth is observed in cumulative discovery estimates based upon 2P reserves in many regions of the world. Also, numerous studies document the importance of technological and geological factors in contributing to reserve growth. These sources may therefore be expected to make a major contribution to future global oil supply.
- *Reserve growth varies widely between different types of fields and could change significantly in the future*: Reserve growth appears to be greater for larger, older and onshore fields, so as global production shifts towards newer, smaller and offshore fields the rate of reserve growth may decrease in both percentage and absolute terms. At the same time, higher oil prices may stimulate the more widespread use of EOR techniques that have the potential to substantially increase global reserves. The suitability of such techniques for different sizes and types of field and the rate at which they may be applied remain key areas of uncertainty.

- *The USGS study provides the best available estimate of future reserve growth at the global level*: The USGS acknowledges that their 'forecast' is not meant to be anything other than a rough estimate using inadequate data and some sweeping assumptions. Contrary to the expectations of some commentators, the global average reserve growth observed since 1995 seems broadly in line with the USGS assumptions. This does not validate those assumptions (after all, it is possible that the errors simply cancelled each other out) but it does give some confidence in short-term forecasts. However, since the global average is strongly influenced by reserve growth in countries with both the largest reserves and the poorest quality data, there are still questions over whether the observed reserve growth is 'real'.
- *The USGS study does not adequately quantify uncertainty*: Although every effort is made by the USGS to assess the uncertainty of their results, the final statement in terms of F5 and F95 fractiles is not only inconsistent with reserve definition standards, but also meaningless when results are quoted in other publications unless the assumed triangular probability distribution is also specified. It would be better to quote the mean (equivalent in this case to the F50) and standard deviation - namely 612±250 Gb for the world excluding US. This is a simpler and more intuitive presentation which is also more likely to be retained when results are quoted out of context.
- *Long-term forecasts of reserve growth will remain highly uncertain unless better data can be obtained*: If reliable field-level data for a world-wide sample of major producing countries were available, it would be possible to estimate reserve-growth functions more accurately and thus improve regional as well as global estimates of the future potential for reserve growth. Although there may be questions over its reliability, this data should in principle be available within the industry databases. Hence, there is a need for those groups who have access to this data to examine regional and global reserve growth in more detail.

References

Arps, J. J., M. Mortada, and Q. E. Smith. (1970). "Relationship between proved reserves and exploration effort." Society of Petroleum Engineers Paper SPE2995, 45th Annual Fall Meeting (Houston). Society of Petroleum Engineers.

Arrington, J. R. (1960). "Predicting the size of crude reserves is key to evaluating exploration programs." *Oil and Gas Journal*, **58**:9, pp. 130-34.

Attanasi, E. D. (2000). "Growth in conventional fields in high cost areas: a case study." *World Oil*, **221**:4, pp. 63-68.

Attanasi, E. D. and T. C. Coburn. (2004). "A bootstrap approach to computing uncertainty in inferred oil and gas reserves estimates." *Natural Resources Research*, **13**:1, pp. 45-52.

Attanasi, E. D. and D. H. Root. (1994). "The enigma of oil and gas field growth." *AAPG Bulletin*, **78**:3, pp. 321-32.

Beliveau, D. and R. Baker. (2003). "Reserves Growth: Enigma, Expectation or Fact?": 851-60. Society of Petroleum Engineers (SPE): Denver, CO, United States.

Bentley, R. W., S. A. Mannan, and S. J. Wheeler. (2007). "Assessing the date of the global oil peak: the need to use 2P reserves." *Energy Policy*, **35**:12, pp. 6364-82.

Drew, L. J. (1997). *Undiscovered Petroleum and Mineral Resources: assessment and controversy* Springer.

Drew, L. J. and J. H. Schuenemeyer. (1992). "A petroleum discovery rate forecast revisited-the problem of field growth." *Nonrenewable Resources*, **1**:1, pp. 51-60.

Forbes, K. F. and E. M. Zampelli. (2009). "Modelling the growth in gas reserves from known fields." *Energy Journal*, **30**, pp. 201-13.

Gautier, D. L. and T. R. Klett. (2005). "Reserve growth in chalk fields of the North Sea; Petroleum geology; north-west Europe and global perspectives; proceedings of the 6th Petroleum geology conference." *6th Petroleum geology conference, London, United Kingdom, Oct. 6-9, 2003*, **6**, pp. 169-75.

Gautier, D. L., T. R. Klett, and B. S. Pierce. (2005). "Global significance of reserve growth." 25. U. S. Geological Survey, Reston, VA, United States (USA): United States (USA).

Grace, J. D. (2007). "A closer look at field reserve growth: science, engineering, or just money?". Bergan et al, Inc.: Rockport, Texas.

Hubbert, M. K. (1967). "Degree of Advancement of Petroleum Exploration in United States." *AAPG Bulletin*, **51**, pp. 2207-27.

IEA. (2005). "Resources to Reserves - Oil and Gas Technologies for the Energy Markets of the Future." International Energy Agency: OECD, Paris.

IEA. (2008). "World Energy Outlook 2008." International Energy Agency, OECD: Paris.

Klett, T. R. (2003). "Graphical comparison of reserve-growth models for conventional oil and accumulation." F1-F63. U. S. Geological Survey, Reston, VA, United States (USA): United States (USA).

Klett, T. R. (2005). "United States Geological Survey's reserve-growth models and their implementation." *Natural Resources Research*, **14**:3, pp. 249-64.

Klett, T. R. and D. L. Gautier. (2005). "Reserve growth in oil fields of the North Sea." *Petroleum Geoscience*, **11**:2, pp. 179-90.

Klett, T. R., D. L. Gautier, and T. S. Ahlbrandt. (2005). "An evaluation of the U. S. Geological Survey world petroleum assessment 2000." *AAPG Bulletin*, **89**:8, pp. 1033-42.

Klett, T. R. and J. W. Schmoker. (2003). "Reserve growth of the world's giant oil fields; Giant oil and gas fields of the decade, 1990-1999." *AAPG Memoir*, **78**, pp. 107-22.

Klett, T. R. and M. K. Verma. (2004a). "Reserve growth in oil and gas fields of Mexico (abst.): Am." *Assoc. Petroleum Geologists Intern. Conf. and Exhibition (Cancun, Mexico).*

Klett, T. R. and M. T. Verma. (2004b). "Reserve growth in oil and gas fields of Mexico." *AAPG Internal Conference and Exhibition*: Cancun, Mexico.

Laherrère, J. (1999). "Reserve growth: technological progress, or bad reporting and bad arithmetic?" *Geopolitics of Energy*, **22**:4, pp. 7-16.

Laherrère, J. (2001). "Is the USGS 2000 Assessment Reliable?" published on the cyberconference of the WEC.

Laherrère, J. (2006). "Oil and gas, what future?" *Groningen Annual Energy Convention*: Groningen, 21 November 2006.

Lore, G. L., K. M. Ross, B. J. Bascle, L. D. Nixon, and R. J. Klazynski. (1996). "Summary of the 1995 assessment of the conventional recoverable hydrocarbon resources of the Gulf of Mexico and Atlantic Continental Shelf." OCS Report MMS 96-003, Appendix A. Minerals Management Service.

Marsh, R. G. (1971). "How much oil are we really finding." *Oil & Gas Journal*, **69**:14, pp. 100-04.

Mills, R. M. (2008). *The myth of the oil crisis*. Westport, CT, USA: Praeger Publishers.

Nehring, R. (1984). "Estimating reserve growth; opportunities and challenges for petroleum resource assessment; AAPG annual convention with divisions; SEPM/EMD/DPA." *AAPG annual convention with divisions; SEPM/EMD/DPA, San Antonio, TX, United States, May 20-23, 1984*, **68**:4, pp. 511.

NPC. (2007). "Facing the Hard Truths about Energy: a comprehensive view to 2030 of global oil and natural gas." National Petroleum Council: Washington, DC.

Odell, P. R. (1973). "The future of oil: a rejoinder." *Geographical Journal*, **139**:3, pp. 436-54.

OGCB. (1970). "Reserves of Crude Oil, Gas, Natural Gas Liquids and Sulphur, Province of Alberta." Oil and Gas Conservation Board.

Pelto, C. R. (1973). "Forecasting ultimate oil recovery." *Symposium on petroleum economics and evaluation, Society of Petroleum Engineers of AIME* 45-52: Dallas.

Pike, R. (2006). "Have we underestimated the environmental challenge?" *Petroleum Review,* **June**, pp. 26-27.

Root, D. H. and R. F. Mast. (1993). "Future growth in know oil and gas fields." *AAPG Bulletin*, **77**:3, pp. 479-84.

Salameh, M. G. (2004). "How realistic are OPEC's proven oil reserves? ." *Petroleum Review*:August.

Sandrea, R. and I. Sandrea. (2007). "Global oil reserves: recovery factors leave vast target for EOR technologies." *Oil and Gas Journal*:November 05.

Schmoker, J. W. (2000). "Reserve growth effects on estimates of oil and natural gas resources." 2. U. S. Geological Survey, Reston, VA, United States (USA): United States (USA).

Schmoker, J. W., T. R. Klett, and W. E. A. T. U. S. U. S. Geological Survey. (2000). "Estimating potential reserve growth of known (discovered) fields; a component of the USGS world petroleum assessment 2000; U. S. Geological Survey World Petroleum Assessment 2000; description and results." 19. U. S. Geological Survey, Reston, VA, United States (USA): United States (USA).

Schuenemeyer, J. H. and L. J. Drew. (1994). "Description of a discovery process modelling procedure to forecast future oil and gas incorporating field growth." ARDS v 5.01. 98-111. US Geological Survey, Open File Report.

Sem, T. and D. Ellerman. (1999). "North Sea reserve appreciation, production and depletion." MIT-CEEPR 99-011. Centre for Energy Environmental Policy Research, Massachusetts Institute of Technology: Cambridge.

SPE. (2007). "Petroleum Resources Management System." Society of Petroleum Engineers, American Association of Petroleum Geologists, World Petroleum Council, and Society Petroleum Evaluation Engineers.

Stark, P. H. and K. Chew. (2005). "Global oil resources: issues and implications." *The Journal of Energy Development*, **30**:2, pp. 159-70.

Tennyson, M. E. (2002). "Regional patterns of growth of United States giant oilfields 1945-1998: influence of reservoir drive mechanisms and recovery technology." *American Association of Petroleum Geologist Annual Conference*: Houston.

Thompson, E., S. Sorrell, and J. Speirs. (2009). "Definition and interpretation of reserve estimates." UKERC review on Global Oil Depletion: Technical Report 2. UK Energy Research Centre: London.

USGS. (2000). "USGS World Petroleum Assessment 2000: description and results by USGS World Energy Assessment Team." USGS Digital Data Series DDS-60 (four CD-ROM set). U.S. Geological Survey: Reston, VA, USA.

Verma, M. K. (2005). "A new reserve growth model for United States oil and gas fields." *Natural Resources Research (New York, N.Y.),* **14**:2, pp. 77-89.

Verma, M. K. and G. F. Ulmishek. (2003). "Reserve growth in oil fields of West Siberian Basin, Russia." *Natural Resources Research (International Association for Mathematical Geology)*, **12**:2, pp. 105-19.

Watkins, G. C. (2002). "Characteristics of North Sea oil reserve appreciation." *The Quarterly Review of Economics and Finance*, **42**:2, pp. 335-72.