Uncertainties in estimating remaining recoverable resources of conventional oil

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Abstract

Numerous uncertainties exist in estimating the remaining recoverable resources of conventional oil held by countries. These uncertainties include: the use of ambiguous definitions and inclusion of different subcategories of conventional oil by reporting sources, the inclusion of political reserves in 1P reserve estimates, the inconsistent and unclear effects of aggregation of field-level 2P reserve data to country and regional estimates, the anticipated volume of undiscovered oil, and the nature and extent reserve growth and its allocation to individual countries. These uncertainties are analysed and literature discussing them reviewed. Industry and academic estimates for reserves, undiscovered oil and reserve growth are examined and allocated to individual countries and it is concluded that it is possible to estimate global remaining recoverable resources, but only with large errors. The procedure for this encompasses a method for incorporating USGS undiscovered oil data released since its 2000 World Petroleum Assessment taking account of discoveries since 1996, accompanied by a procedure for allocating remaining reserve growth to individual countries.

1 Introduction

A significant volume of work has previously been carried out analysing estimates of remaining recoverable resources of conventional oil. Unfortunately this is a contentious area and analysis is often pigeonholed into either an 'optimistic' or 'pessimistic' camp (based upon views of long term supply availability), with work in both camps exposed to polarised criticism often based upon selective or biased evidence. This area is therefore not often assessed, at least in the public arena, in a methodical, rigorous and scientific manner.

The goal of this paper is therefore to analyse and review any uncertainties in determining estimates of remaining recoverable resources of conventional oil held by individual countries (not regions) in an objective manner, and, if possible, produce a country-level database of these resources.

The recent work of Sorrell et al. (2009) set out to examine the evidence discussing the likelihood for a near term peak in conventional oil production before 2030. This paper builds on that work, but does not discuss production profiles and hence does not analyse 'peak oil' to any degree, however it does draw on evidence presented both by the 'optimists' and by the 'pessimists'.

Before examining the major uncertainties in estimating countries' remaining recoverable resources, it is first necessary to define and explain what is meant by the terms 'conventional oil' and 'remaining recoverable resources' as one uncertainty that can exist arises from the differing use of these terms by analysts.

1.1 Definitions

1.1.1 Conventional oil

Conventional oil encompasses a variety of types of oil but the best known is 'crude oil', which the EIA (2009) defines as *'A mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities...'*. Numerous other oils of varying density, viscosity, source and production techniques exist, which are as listed below:

- crude oil;
- lease condensate;
- Natural Gas Liquids (NGL);
- extra-heavy oil;
- oil sands;
- oil shale; [1]
- shale oil; [2]
- gas-to-liquids (GTL);
- coal-to-liquids (CTL); and
- biofuels

As mentioned, shale oil and synthetic oil produced from oil shale are often confused. However, for ease of reference and since both currently contribute very little to global reserves, I shall adopt a terminology whereby any mention of shale oil in the remainder of this text also includes this synthetic oil produced from oil shale.

The above subcategories can be grouped together into either 'conventional oil', 'unconventional oil',[3] or 'unconventional liquids', however disagreement exists over the composition of these groups. Conventional oil is generally accepted to include crude oil $> 20^o$API and condensate. Unconventional oil generally includes

[1] Oil shale is a bit of a misnomer in that oil shale is not really a shale and does not really contain any oil. The source rocks are in fact a mudstone that contain an organic compound called kerogen (Mohr and Evans, 2010). Some analysts refer to the shale containing the kerogen as 'oil shale' and the synthetic oil that can be produced from it as 'shale oil' (Dyni, 2006). This terminology leads to considerable confusion, however, as shale oil is a totally different category of oil.

[2] Shale oil actually has a lot more in with shale gas, an unconventional gas also produced from shale, than synthetic oil produced from oil shale.

[3] The term non-conventional is also sometimes used instead of unconventional

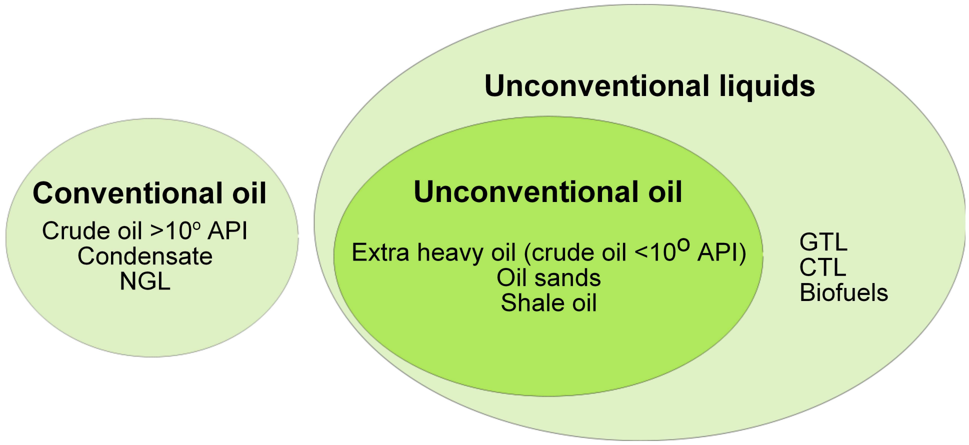


Figure 1: Definitions of liquids used in this report

Source: adapted from Sorrell et al. (2009)

extra-heavy oil, oil sands and shale oil, while unconventional liquids incorporate these as well as CTL, GTL and biofuels. The remaining controversial categories are therefore NGL and heavy ($10-20^o$API) oil. NGL is sometimes combined with conventional oil and sometimes reported separately by e.g. Ahlbrandt et al. (2000) in the United States Geological Society (USGS) 2000 World Petroleum Assessment. Meanwhile, sources can include different portions of heavy oil in either category. Rempel from the German Federal Institute for Geosciences and Natural Resources (BGR), for example, reported that BGR formerly counted heavy oil as unconventional but in its most recent report (BGR, 2009) included it in conventional oil, adding that this is somewhat of a *'grey area'* (priv.communication). To further complicate matters, Campbell and Heapes (2009) have a very stringent definition of conventional oil which excludes oil $< 17.5^o$API, oil found in deepwater (> 500m) or polar conditions, NGL from gas plants, and shale oil and oil sands.

We shall adopt the definitions of Sorrell et al. (2009) whereby conventional oil includes NGL, condensate and any crude oil $> 10^o$API not including shale oil or oil sands as shown in Figure 1. No distinction is made whether the oil is found in deepwater or polar conditions or not. We also make the distinction of 'conventional crude oil', which is solely crude oil $> 10^o$ API and excludes condensate, NGL and all unconventional liquids, to avoid any confusion over the use of the term crude oil.

1.1.2 Remaining recoverable resources

The term 'remaining recoverable resources' is used by numerous authors and organisations (Sorrell et al., 2009; IEA, 2008) to mean the remaining volume of oil in a region or country that can still be produced. Remaining recoverable resources are defined as the difference between the ultimately recoverable resources

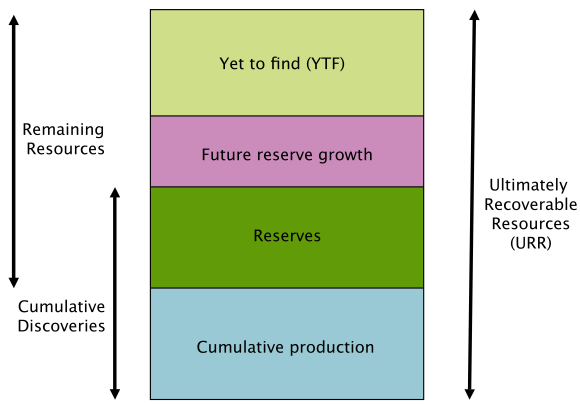


Figure 2: Relationships between remaining resources, ultimately recoverable resources and cumulative discoveries

Source: Sorrell et al. (2009)

(URR)[4] for a region and that region's cumulative production (Sorrell et al., 2009). The URR is the total volume of oil that is estimated to be economically producible from a field, country or region from the time when production first begins until it ceases. Cumulative production is the total volume of oil so far produced. BP (2009) reports that the URR is only an estimate of the total volume of oil recoverable and could change with varying technology, economics and knowledge, but that this is disputed by some authors. Figure 2 represents the relationship between URR, remaining recoverable resources, and cumulative discoveries.[5]

2 Sources reporting reserve data

There are numerous sources providing data or information of varying scope and quality that can be used to determine an individual country's oil reserves. The list below includes all publications to which I have access or that I have consulted. Some of these publish information on an annual basis and so the date indicated represents either the date of publication or of the latest revision. In addition to these, there are a number of industry or consulting firms that provide such information, with the two best known and most comprehensive databases compiled by Wood MacKenzie and IHS Energy (Sorrell and Speirs, 2009). Unfortunately these are extremely expensive.

- Oil and Gas Journal, 2010;
- World Oil, 2009;

[4]Some authors such as BGR (2009) use the term 'estimated ultimate recovery (EUR) for URR. This is probably a better term as it conveys the estimated nature of the total volume of oil recoverable.

[5]URR is often determined through the use of analytical and statistical processes involving 'curve fitting' functional forms to existing field data. Sorrell and Speirs (2009) give a detailed description of each procedure that can be used accompanied by a comparison of results. These procedures shall not be discussed further in this paper.

- BP Statistical review, 2009;
- OPEC annual statistical bulletin, 2008;
- World Energy Council, 2009;
- BGR (German Federal Institute for Geosciences and Natural Resources), 2009;
- World Petroleum Assessment 2000 - Description and Results by U.S. Geological Society, 2000;
- IEA, 2008;
- EIA, 2009;
- 'Crude Oil - The Supply Outlook' by the Energy Watch Group, 2008; and the
- 'Atlas of Oil and Gas Depletion' by Campbell and Heapes, 2008.

This section aims to identify the key problems with the sources listed above that lead to uncertainties in estimating a country's reserves. This begins at §2.1 with an explanation of the various definitions of reserves and resources. This is followed by a summary and explanation of the liquids included in each of the sources at §2.3. Literature commenting on the phenomenon of political reserves is reviewed at §2.4, and finally a table summarising the make up of data reported by each is presented.

2.1 Defining reserves and resources

Laherrere (2006) states that the terms 'reserves' and 'resources' are often confused. This can be prevented, however, by examining Figure 3 below - the 'McKelvery Box'. The McKelvery Box shows that resources are some estimate of the total amount of oil that is present, including those fields that have been discovered but are not currently considered economically viable. Reserves on the other hand should be viewed as the *'commercially exploitable oil that is in-situ'* (Owen et al., 2010), i.e. some portion of the resources that it is economically viable to produce. As can be seen from the diagram, reserves can be further split into 1P, 2P and 3P which are respectively associated with the terms 'proved','proved and probable' and 'proved, probable and possible' (Sorrell et al., 2009).

That is unfortunately the extent of agreement between sources reporting reserves. Despite using similar language and terms such as 1P, 2P and 3P, the meanings of these as well as precise definitions of 'resources' vary widely between sources whenever used. The major inconsistency between reporting companies or countries are whether they adopt a deterministic or probabilistic definition, although even within each camp inconsistencies exist in the precise deterministic or probabilistic definitions used (Thompson et al., 2009).

These differences, particularly between countries' reserve reporting standards lead to uncertainties in reserve estimates due to the nature by which a number of the reporting agencies listed above collect their data. The Oil and Gas Journal, for example, which is generally assumed to report 1P reserves (Thompson

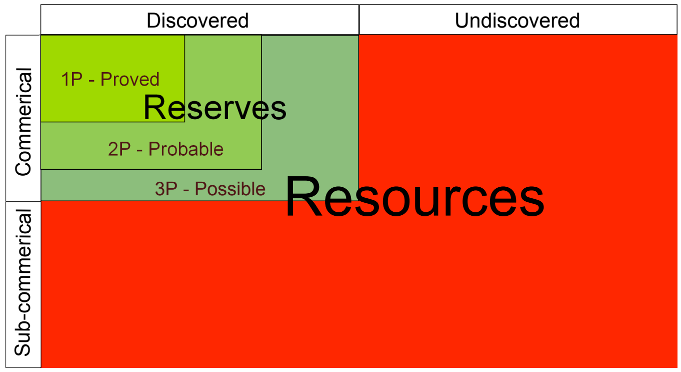


Figure 3: The McKelvery box indicating the relationship between reserves and resources

Source: McKelvery (1972)

et al., 2009), obtains its data by distributing survey sheets to countries and asking for them to be completed and returned. The large variation in definitions that the individual countries could use means that it is not necessarily insightful or even appropriate to compare one counties' reserves with another's as aggregation of such data would be systematically flawed.

Even if two countries were to use the same deterministic definition, one country could interpret the meaning of for example 'reasonable certainty' differently from the other, compounding this systematic error. This uncertainty can, however, be countered if both countries were to use probabilistic definitions as these have inherently more precise meanings.

2.2 Aggregation of reserve data

If the reserves reported are interpreted using the probabilistic method, a different problem can arise however. Under the SPE/PRMS definitions, 1P, 2P and 3P reserves are associated with the statistical relationships P90, P50 and P10, with a P90 reserve estimate to be interpreted as the volume of oil that has 'a 90% chance being exceeded' and similarly for P50 and P10. Due to the statistical nature of 1P, 2P and 3P reserves, individual countries' 1P estimates cannot simply be arthimetically summed to give an aggregate 1P estimate for a larger region. At every stage of aggregation (field to region to country to globally) there is a systematic underestimation of the true aggregate 1P estimate (Thompson et al., 2009). The opposite is true with 3P estimates whereby aggregation by arthimetic summing leads to a systematic overestimation of the true 3P reserve estimate. This is illustrated very lucidly by Pike (2006) and Jung (1997) using two dice. When the dice are rolled separately, the probability of exceeding one is 83% or P83 in statistical notation. However, when the two dice are rolled together, the P83 figure is now four, i.e. the aggregate P83 figure is not the sum of the two individual P83 figures. Another way of expressing this using dice is that an aggregate value produced by the arithmetic sum of ten P60 events is actually P80. Therefore interpreting the arthimetic sum of ten P60 events as P60 would systematically underestimate the true P60 value. The effect of aggregating 1P (P90) estimates by arthimetic summing is even more marked as these are statistically much further from the mean than P60 values, yet this is unfortunately common practice. Thompson et al. (2009) indicate therefore that regional 1P estimates are liekly to be *'significantly understated'* while regional 3P estimates are *'significantly overstated'*.

Problems can also occur when aggregating 2P estimates, which, as mentioned above, are usually identified as the P50 or median estimate. In aggregating individual fields one can arithmetically sum mean estimates, not median estimates. Whether the mean and median are equal depends on the underlying probability distribution for that geological region, which in turn depends upon the nature of the relationship between field sizes and numbers within the region - a subject of considerable debate.

Finally, Laherrere (2000) indicates that the number of upwards revisions of US field sizes, which were reported as 1P according to the old SEC rules given above, was double the number of downwards revisions, meaning that the 1P estimates actually corresponded to P66 and not P90. A separate study by Jung (1997) indicates that aggregate Canadian companies' reserves were revised upwards in only 60% of circumstances, meaning that aggregate 1P estimates corresponded to P60.

These results lead Sorrell and Speirs (2009) to conclude that reserve estimators are not particularly good at estimating. If the results of these studies are similar across the rest of the world, then aggregation of 1P estimates will still lead to large underestimations of true 1P aggregate estimates but not as large as if the disaggregate estimates were truly P90.

2.3 Variation in included liquids

There are major differences between which of liquids listed above are included in the reserve and production data of the reporting sources, making comparisons difficult. Table 1 compares the groupings of liquids provided by each.

Many sources simply use the term 'crude oil' but do not clarify which of the other liquids are included in this. Unless an alternative is given, I have therefore assumed that they use the definition given at the start of §1.1.1 whereby any contribution from CTL, GTL or biofuels is excluded (as the oil must be in *'liquid phase in natural underground reservoirs'*), but condensate, NGL, extra heavy oil, oil sands, and shale oil are included unless the source explicitly states to the contrary.

There are also inconsistencies in the volumes of unconventional reserves included. For example, according to numerous sources including the USGS (Schenk et al., 2009; Meyer and Attanasi, 2003) the quantity of

Reporting Source	Groupings in reserve data
OGJ	Conventional crude oil, extra heavy oil, condensate, shale oil and oil sands
World Oil magazine	Conventional crude oil, extra heavy oil, condensate, shale oil and oil sands Oil sands from Canada
BP	Conventional crude oil, extra heavy oil, condensate, shale oil, oil sands and NGL Oil sands from Canada
OPEC	Conventional crude oil, extra heavy oil, condensate, shale oil and oil sands[1] Extra-heavy oil from Venezuela
BGR	Conventional crude oil, condensate and NGL[2] Extra-heavy oil, shale oil and oil sands*
WEC	Conventional crude oil[3], condensate and NGL *'where it cannot be separated'* NGL Extra-heavy oil Oil sands Shale oil[4]
IEA	Conventional crude oil, condensate and NGL* Extra heavy oil* Oil sands*
EIA	Does not provide any of its own reserve estimates, but quotes directly from BP, World oil and OGJ
Energy Watch Group	Conventional crude oil, condensate and NGL
Campbell	Crude oil $> 17.5^o$API excluding shale oil, CTL, deepwater oil, polar oil, and NGL from gas plants Crude oil $< 15^o$API, shale oil, CTL, deepwater oil, polar oil, and NGL from gas plants
USGS	Conventional crude oil $> 17.5^o$API NGL
IHS	Conventional crude oil, extra heavy oil, NGL, condensate, and oil sands

Sources: OGJ, World Oil, BP (2009), OPEC (2008) ,BGR (2009), WEC(2007), IEA (2008), Schindler and Zitell (2008), Campbell and Heapes (2009), USGS (Ahlbrandt et al., 2000)

* Data provided at a regional or aggregate level

1 Provides 'conventional crude oil' only for Canada but leaves this undefined

2 BGR states in the glossary of its report that conventional oil is defined as $> 20^o$ API yet a diagram on page 82 appears to show it as $> 10^o$ API. As described in the main text above, a personal communication from BGR indicated that it now defines crude oil $> 10^o$ API as conventional

3 WEC states that any crude oil with viscosity $> 10,000$cP is dealt with in the natural bitumen and extra-heavy oil tables. However, given the definition of extra-heavy oil ($< 10^o$ API and viscosity $< 10,000$cP), it is unclear whether this is included or not in the conventional crude oil table.

4 WEC gives shale oil resources but no indication of what percentage could be converted to reserves

Table 1: Liquids contained in each of the reporting sources

unconventional oil in place and resources in Venezuela and Canada are of a similar order of magnitude, yet the OGJ includes 172Gb (billion barrels) of unconventional oil sands/natural bitumen for Canada but only appears to assign around 15Gb to Venezuela for its heavy and extra-heavy oil reserves. It is also often difficult to assess the volume of unconventional reserves that have been included in the reserve estimates of a number of counties or indeed whether these have been included at all. This makes it difficult to determine a database of purely conventional reserves using any of the sources that mix conventional and unconventional oil without indicating any sort of apportionment to one or the other.

2.4 Political reserves

'Political reserves' are reserves declared by a country or company that do not correspond to the reserves it possesses but are those which it would like to convey to the rest of the world. 'Political reserves' is a term coined by Laherrere (2006).

There is particular and much reported concern (IEA, 2008) with reserves declared by the member states of OPEC in its Annual Statistical Review (OPEC, 2008). As can be seen in Figure 4, a major increase in OPEC's reserves occurred in 1985-1990 despite no new discoveries being reported (Schindler and Zitell, 2008). The explanation given by OPEC was that reserve assessments were previously too low and that this jump was simply a correction of this underreporting. Some analysts agree that this was justified to an extent given that the international oil companies operating in these countries prior to nationalisation *'perhaps had a tendency to underreport reserves for financial and political reasons'* (Schindler and Zitell, 2008). Another explanation is that between these dates the countries started to report original and not remaining reserves (WEC, 2007).

One hypothesis, however, appears to be prevalent amongst analysts (Owen et al. (2010); Sorrell et al. (2009)). The step increase coincided with OPEC's decision in 1985 to set production quotas partly in accordance with remaining reserves, incentivising the member countries simply to report unrealistically high reserves in order to obtain a higher production allowance. This viewpoint is supported by OPEC's continuous declarations that reserves in its member countries have been maintained at more-or-less the same levels since this jump despite continuing production. This static data led the IEA (2005a) to comment in 2005 that *'the level of remaining reserves of oil has been remarkably constant historically, in spite of the volumes extracted each successive year . . . The addition of new reserves has therefore roughly compensated for consumption.'*, a statement which drew much criticism from Bentley et al. (2007).

Of particular concern are the declared 1P reserves of Kuwait. In OPEC's 2008 report, these were reported as 101.5Gb (having been at exactly this level since 2004) (OPEC, 2008), while IEA (IEA, 2005b), the Energy

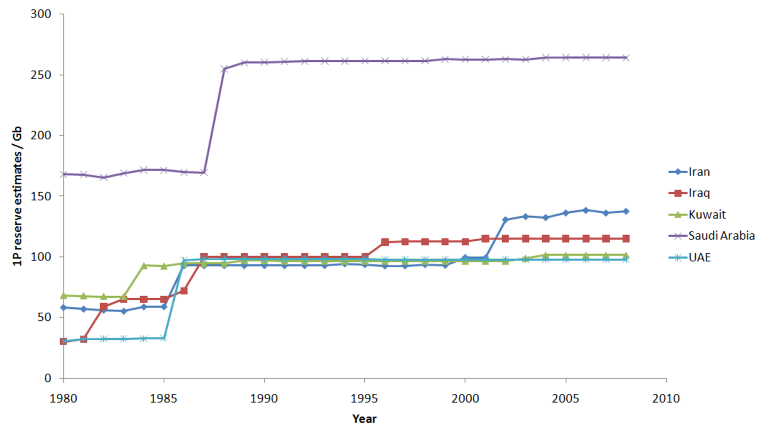


Figure 4: 1P reserve estimates of OPEC countries between 1980 and 2008

Source: OPEC (2008)

Watch Group (Schindler and Zitell, 2008) and Campbell and Heapes (2009) all reported that its 2P reserves were closer to 50Gb, a difference of over 50Gb.

The possibility of OPEC reserve inflation is interpreted in different ways by analysts. Some, such as Campbell and Heapes (2009) tend to discount OPEC reserves by a large degree (for example by around 110Gb for Saudi Arabia), while others such as Watkins (2006) take them at face value, implying that they agree with the IEA in considering that reserve growth (see below) and new discoveries have essentially matched production since the step increases.

Disagreement also exists over the level of Russian reserves. Russia not only uses a different reserve classification system from most other countries, but also strongly protects official 'true' reserve estimates. In 2003, Laherrere (2003) indicated that *'When FSU [Former Soviet Union] oil reserves were evaluated by Western consultants, it was found that these values have to be reduced by 30%.'*, while only one year later Felder (2004) from IHS indicated that the Russian official sources *'are considered pretty reliable.'*. This discrepancy appears not to have been resolved even four years later, as the World Energy Council (2007) again repeated that *'The categories A + B + C1 are widely considered equivalent to the proved + probable reserves... but decline studies of individual fields suggest that in fact they exaggerate by about 30%.'*

2.4.1 Summary table

Bentley et al. (2007) and Thompson et al. (2009), both consider that estimates of global remaining reserves should be made using 2P instead of 1P data. Given the above, I agree. I also consider, however, that sources that report 1P reserves, which have made no attempt to verify their data, which are based upon disparate and uncertain definitions, that cannot be aggregated, and which propagate the reporting of meaningless

Source	Reserve class	Data aggregation	Major liquid grouping
OGJ	1P	Country	Conventional & unconventional oil
World Oil magazine	1P	Country	Conventional & unconventional oil
BP	1P	Country	Conventional & unconventional oil
OPEC	1P	Country	Conventional & unconventional oil
BGR	2P	Country	Conventional oil
WEC	1P	Country	Conventional oil
IEA	2P	Regional	Conventional oil
Energy Watch Group	2P	Country	Conventional oil
Campbell	2P	Country	'Regular conventional oil'
IHS	2P	Country	Conventional & unconventional oil

Sources: OGJ, World Oil Magazine, BP (2009),OPEC (2008) , BGR (2009), WEC (2007), IEA (2008), Schindler and Zitell (2008), Campbell and Heapes (2009), USGS Ahlbrandt et al. (2000) and IHS

Table 2: Summary of information contained in each reporting source

political reserves are essentially useless for the task of assessing the global endowment of oil.

The sources I prefer to use would ideally: provide easy differentiation between conventional and unconventional reserves, use a 2P probabilistic definition, take account of, and if necessary allow for, the potential for political reserves, produce their own data (not relying upon countries' own declarations) provide data at a disaggregate country level, and be audited. The most suitable sources from the table are therefore BGR, EWG, Campbell and IHS. There are individual problems with each of these however.

Campbell's very narrow definition of conventional oil means that it is difficult to compare his estimates with the others. He does, however, mention those countries that have offshore or polar oil reserves and gives an indication of the extent of these. His conservative definition can therefore be modified to include polar and deepwater oil by adding these 'non-regular oil' estimates back into to his reserve figures. Nevertheless, Campbell's including oil only $> 17.5^o$API and, significantly, excluding NGL means that his figures will be at the lower end of the scale when comparing the useful reporting sources.

I suspect that BGR's reserve estimates are mainly taken from publically available data sources, as its reserve estimates in a large number of countries match the public 1P data. A problem with the IHS data is that it contains unconventional oil, although from analysis of the data this only appears to affect Venezuela as the IHS reserves for Canada are less than EWG's purely conventional volumes.

It can be seen that the most suitable reserve reporting source is likely to be EWG but the other three sources do provide useful information for comparison.

3 Reserve growth

Reserve growth is defined as *'the commonly observed increase in recoverable resources in previously discovered fields through time'* (Klett and Schmoker, 2003). The term reserve growth is a little confusing as the volume of reserves in the ground are constantly being depleted due to production and increasing with discoveries of new fields. Reserve growth, which excludes any contribution from new field discoveries, is therefore actually growth of the initial reserve estimate or of the total volume of oil recoverable.

When a field increases in size, a reporting source can either assign the increase to the year that the reserve growth occurs or to the year that the field was discovered. The logic behind the first of these approaches is that the oil did not become available until the growth actually occurred, while the logic behind the latter, called 'backdating discoveries', is that the field was originally that grown size when discovered and backdated data therefore presents a more accurate representation of what was really discovered, even if it was not fully appreciated at the time.

It is best to study reserve growth by analysing successive versions of a 2P reserve database, such as that produced by IHS, from which new discoveries in a region can be separated from reserve growth in existing fields (Thompson et al., 2008). This distinction is most easily made if the reserve estimates are backdated to the time of discovery of the field.

In order to calculate the amount of reserve growth in a field, country or region between two years, one subtracts the reserve estimate in a given year indicated in the first database from the estimate for the same area and same year indicated in the second database. The areas and years that are subtracted must exactly match or new field discoveries and ongoing production will vitiate the results. This can be illustrated by reference to the schematic Figure 5. The arrow indicates the reserve growth that has occurred between 1995 and 2000 for fields discovered up to 1995. Similarly, an arrow between the 1995 and 2005 lines would represent the the reserve growth that has occurred between 1995 and 2005 for fields discovered up to 1995.

This is the standard method for examining reserve growth, however it results in one problem: this method sums, and does not distinguish between, two types of mechanisms by which reserve estimates for a country can increase.[6]

The first of these mechanisms arises from a reporting agency's including new and revised data in its estimates, in other words reserves being added through more comprehensive accounting of fields contributing to reserves, and it is often termed 'reporting' reserve growth. As an example, Stark and Chew (2005) indicate that new information came to light that allowed IHS to include fields in South America, the Middle East and

[6] As mentioned above, reserve estimates for a country or region can also increase from new discoveries and decrease due to continuing production, however these are excluded by the method indicated.

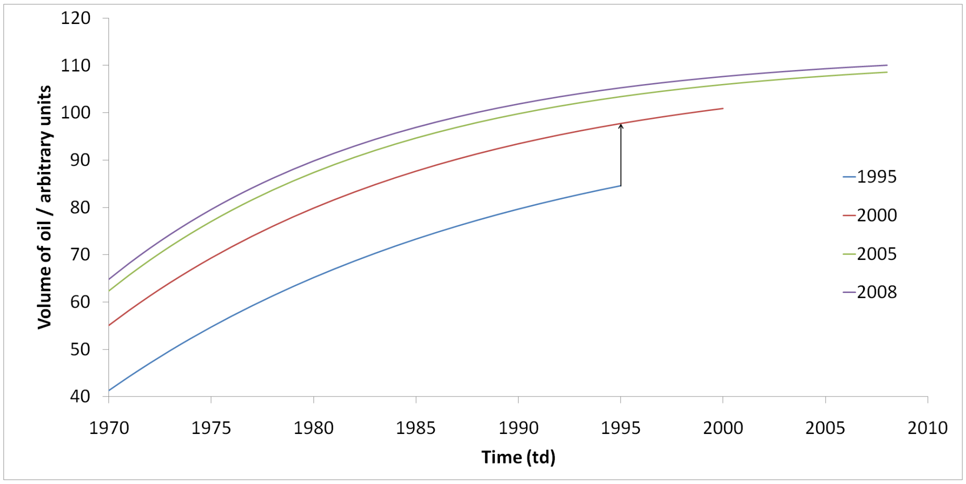


Figure 5: Schematic representation of cumulative discoveries as reported by a successive set of databases. Each line represents the cumulative discoveries as reported by a database in the designated year. The arrow indicates the reserve growth that has been experienced from 1995 to 2000 in all fields discovered before 1995.

the Former Soviet Union that had been previously excluded, which manifest as reserve growth. This type of reserve growth is therefore a result of IHS's (or any other reporting agency who produce data in such a way) *'continuous effort to enhance the completeness and quality of historic fields'* and has not resulted from any real changes in understanding or technology (Thompson et al., 2008). 'New and revised data' could also result from the decisions of a reporting source to include unconventional oil where it had not previously. For example, OGJ decided to include around 170Gb of Canadian oil sands in its reserve estimates for Canada in 2002. Since these were not 'discovered' in 2002, this increase would have appeared as reserve growth.

The second reserve growth mechanism is often referred to as 'classic' reserve growth (Stark and Chew, 2005) or 'real field growth' (Bentley et al., 2007). See §3.2 below for a list of factors incorporated in this. Reserves added to estimates in this way do not result from any accounting changes but from new reserves that were not previously considered economically, technologically, geologically or definitionally viable becoming available to be produced. The contribution of each of these types of reserve growth can be significant. Stark and Chew (2005), for example, indicate that there were about 290Gb of 'reporting' reserve growth between 1995 and 2003 and 175Gb 'classic' reserve growth.

When determining reserve growth using the above method, it is therefore important for analysts to: differentiate between 'classic' and 'reporting' reserve growth, separate these, and explain how they made this distinction. Unfortunately analysts rarely undertake all of these steps (Thompson et al., 2008; Stark and Chew, 2005), as discussed in more detail at §3.3 below. In the following sections, we discuss 'classic' reserve growth only.[7]

[7]Any contribution from 'reporting' reserve growth, which could in a way be considered to be a systematic error, will be

3.1 Criticism of reserve growth and reserve growth functions

Much analysis focuses on examining and predicting reserve growth using 'reserve growth functions'. Derived using a statistically significant number of fields, reserve growth functions are a functional form that predicts by how much fields will grow in the years after they are discovered.

The usefulness of reserve growth functions to predict future reserve growth is debated however. Figure 6, taken from Verma and Ulmishek (2003), for example displays a number of different field reserve growth functions, which can be seen to vary considerably between fields in different regions, whether they are onshore or offshore, and the time that the reserve growth function was constructed. Thompson et al. (2008) indicate also that reserve growth functions, and therefore estimates of future reserve growth determined using them, can be expected to vary between:

- fields of different sizes;
- fields of different ages;
- fields of different types;
- fields of different owners; and
- fields in different regions.

Campbell and Heapes (2009) and EWG (Schindler and Zitell, 2008) on the other hand do not make any explicit allowance for reserve growth. Bentley et al. (2009) report that Campbell and EWG consider that the 2P reserve estimates already include an allowance for future reserve growth but adds that Campbell *'does not dismiss'* the long term importance of reserve growth driven by technical progress.[8]

3.2 Other approaches to reserve growth

Substantial reserve growth does appear to have been experienced throughout the world (see §3.3 below), but the above reservations concerning the use of reserve growth functions do appear to be wide ranging and valid and questions must be asked of their use. There is therefore a need to examine the factors that can influence reserve growth in more detail.

Verma (2007) (of the USGS) supports this approach, reporting that the USGS acknowledges that reserve growth should not be estimated using only one reserve growth function: *'it became obvious that use of the U.S. [RGF] model would not necessarily give correct reserve growth potential for all other areas [throughout*

unpredictable but likely to decline as fewer fields are missed out of the IHS database.

[8] When determining remaining recoverable resources, it could therefore be argued, that since they consider that it is already accounted for, an estimate for reserve growth should not be added to the reserve figures of Campbell and EWG. The curve fitting procedures they use to determine URR and reserves cannot, however, take account of a number of the reserve growth issues discussed below in §3.2. I therefore consider that some aspect of reserve growth must be added to the 2P figures they have derived in order to take full account of potential contributions to remaining recoverable resources.

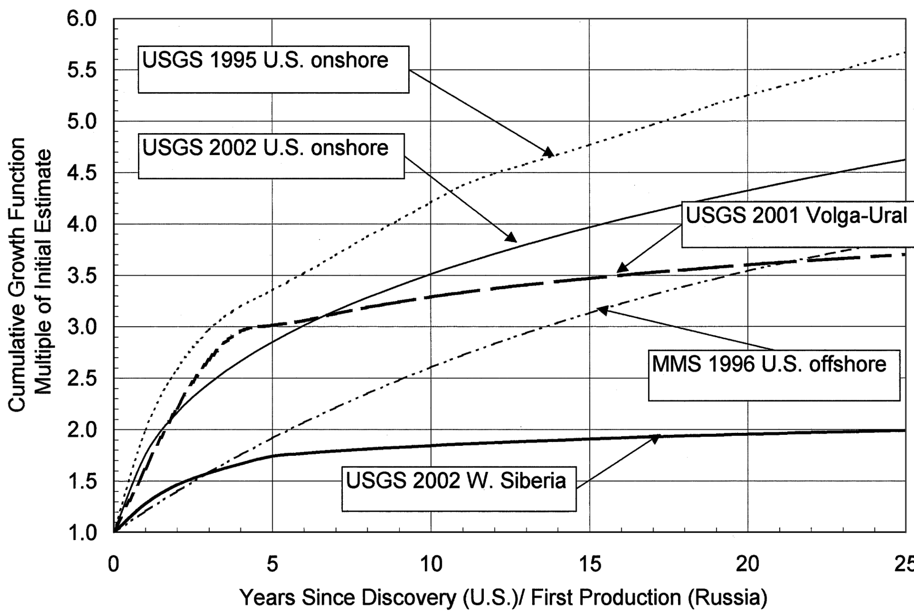


Figure 6: Field reserve growth functions. The variation in field reserve growth functions between region, type and year the field was discovered is evident

Source: Verma and Ulmishek (2003)

the world]' and so *'the USGS is actively pursuing . . . an approach to develop a reserve growth method based on percent depletion rather than time'.*

In addition, Nehring (2007) indicated that between 1964 and 2007 'pressure maintenance'[9] was employed on nearly all applicable fields throughout the world, increasing recovery factors[10] of many giant fields significantly, and indeed doubling it in many cases. He added, however, that there is no real scope for pressure maintenance to further increase recovery factors because it has been adopted everywhere where it might prove to be useful. He therefore concluded that simply projecting a historical rate using a reserve growth function is unreliable and a systematic building up of reserve growth from its constituent parts coupled with forecasting by how much each of these will increase (or decrease) in the future is much more suitable.

The following subsections examine the components that are likely to add to reserve growth:

3.2.1 Definitional factors

Aggregation of median (2P) reserve estimates can lead to an underestimation of the true 2P aggregate estimate if, as described above at §2.2, the mean is greater than the median. There will therefore be some

[9]Pressure maintenance involves pumping water or gas down an oil well in order to artificially increase the pressure in the well. This increases both the rate and absolute magnitude of oil recovery. It is known as secondary recovery, after the primary stage of production using the inherent pressure of the underground oil itself.

[10]The recovery factor is the percentage of the estimate of oil originally in place (OOIP) that is eventually produced over all time i.e. the ratio of URR to OOIP

reserve growth as these underestimated values grow towards the larger 2P aggregate estimate over time. Thompson et al. (2009) indicate that there is no data that shows that the mean is usually greater than the median, which means that there is unlikely to be any reserve growth by this mechanism since the opposite, with the median greater than mean, is just as likely to happen (this lead to an overestimation and possible reserve shrinkage).

Bentley et al. (2007) reports that:

> *'It has long been known that for large fields early public-domain proved plus probable reserves are usually on the conservative side... such early conservatism reflects engineering pragmatism on the size of infrastructure to be built early in a field's life, and also perhaps a wish to avoid being over-optimistic to the market on an asset should problems arise later'*

This could therefore manifest as reserve growth, but any potential contribution would be extremely difficult to determine.

Thompson et al. (2008) indicate two more definitional factors that could contribute to reserve growth. Firstly, reserve reporting definitions can change. For example, the change that occurred in Russian reserves after the collapse of the Soviet Union, and the change currently underway in the US towards the SPE/PMRS definitions. Secondly, fields are sometimes not included in reserve estimates until they receive government production sanction, which Bentley et al. (2007) indicates has occurred in the UK.

3.2.2 Enhanced oil recovery

Enhanced oil recovery from an oil field can take one of three forms (Thompson et al., 2008):

- thermal - introducing heat to alter the characteristics of the oil such as reducing viscosity or increasing pressure;
- gaseous - introducing a gas such as CO_2 or N_2 to achieve a miscible or homogeneous solution of oil, which may decrease the oil's viscosity and increase the oil's mobility or displace any underlying water; and
- chemical - introducing chemical compounds to reduce the 'interfacial tension'.

In order to determine the likely contribution of EOR to reserve growth, a frequently employed method is to calculate an average global recovery factor and increase this by a certain amount (Sandrea and Sandrea, 2007; IEA, 2005a). There are a number of problems with this approach however, with one major problem being the accuracy of determining recovery factors themselves. Falcone et al. (2007) report that these can be affected by whether the estimate is made before or after production starts in a field, whether it is based on 1P or 2P reserves, and on political stances, geology, regulatory guidelines, technology and commercial practices.

The figures for global recovery factors below are estimates made by a number of authors:

- Meling (2003) - 29%
- Laherrere (2006) - 27%
- Sandrea and Sandrea (2007) - 22%
- Nehring (2007) - 34%
- IEA (2008) - 34.5%

These may appear to show relative consistency but IEA (2005a) indicates that *'numbers of this order are often quoted, but rarely supported by abundant data'*. Most of the authors do not indicate whether the recovery factors are derived using 1P or 2P reserves, and with the exception of Sandrea and Sandrea (2007) also appear to include both conventional and unconventional oil in their recovery factors. Unconventional wells generally have much lower recovery factors and would skew the data downwards, which makes the low prediction of Sandrea and Sandrea (2007) quite surprising. As also reported by the IEA (2008), a difference of only 1% in the global recovery factor can make a difference of around 80Gb to global URR. Therefore a range of 12% as represented in the figures below represents a huge uncertainty in assessing any contribution of EOR to reserve growth.

The increment by which EOR might increase a global figure is also debated and the following increases have been proposed:

- IEA (2005a) - 10%, although a more conservative increase in recovery rate of 5% is also given
- Meling (2003) - 9%
- Total (2008) - 5% (reported by (Bentley et al., 2009))
- BP (2008) - 15-20% (reported by (Bentley et al., 2009))

A recent paper by Chenglin et al. (2009) provided a methodology for estimating the recovery factors for oil fields in China. Using statistical analysis of empirical geological and development[11] data in 129 different geological basins, they produced a relationship between the recovery factor and these geological and development characteristics, from which they produced a priority weighting for each characteristic. Each basin, based on its individual characteristics, was then given a weighted score that determined the likely recovery factor of oil from that basin. The results showed that tertiary or EOR recovery had only an 8% influence on increasing the average recovery factor in any basin, significnatly less than the estimated

[11] The development characteristics are the oil recovery mechanisms such as pressure maintenance or thermal methods that have been applied.

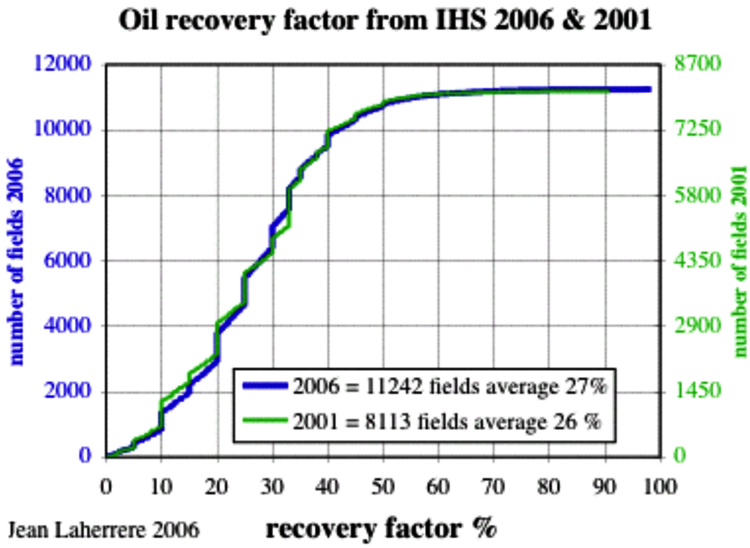


Figure 7: Recovery factors of fields in 2006 and 2001

Source: Laherrere (2006)

60% influence of geological factors. This implies that an increase of 10% or greater in the global recovery factor as suggested by BP might be optimistic.

Finally, Nehring (2007) indicated in 2007 that around 50% of the world's oil fields could use EOR with 11% currently doing so. The contribution that EOR in these 11% of fields would have made to the global recovery factor has presumably already been factored into reserve estimates and so they cannot contribute further to any future reserve growth. This suggests that an increase of 10% in the IEA average world recovery factor of 34.5%, would require an increase in the average recovery factors of the 39% of fields not yet using EOR to above 60%. Although possible, Figure 7 indicates that, historically, very few fields have achieved recovery factors above this level, which again suggests that an increase in worldwide recovery factors greater than 10% might be unachievable.

Given all of the above misgivings, it is clear that recovery factors are not an ideal mechanism to determine the relative contribution of EOR, however since the principle alternative procedure would require very detailed and objective field by field data, most analysts are forced to use them.

3.2.3 Better understanding of the reservoir geology

A better understanding of a reservoirs's geological characteristics through measures such as cross-well, 4D seismic or electromagnetic surveys could lead to an increase in its recovery factor (IEA, 2005a).

Although most of these technologies are not particularly new, they are constantly improving and will continue to help more accurately assess field sizes and potentially lead to an increase in the recoverable reserves. The surveys can indicate for example whether during initial drilling any pools were by-passed and whether they could be accessed using horizontal or multilateral wells (Verma, 2007).

The IEA (2008) indicates that it expects recovery factors to increase from around 35% to 50% due to a combination of secondary recovery, EOR and improvements in geological understanding of resevoirs, but that this was likely to *'take much more than two decades'*. Since the IEA considers that EOR was likely to increase recovery factors by around 10%, this implies that a better understanding of the reservoir geology could increase worldwide recovery factors by 5% or, using its figures, 400Gb. This again appears ambituous.

3.2.4 Oil prices

An increase in oil prices will not only stimulate an increase in EOR and a better understanding of the reservoir geology, but will also lead both to fields continuing to produce for longer even though production rates are very low and to fields that were previously considered to be uncommercial being brought on line (Stark and Chew, 2005). With regards to the first of these two effects, fields are generally shut down once production drops below the rate where operational costs outweigh income from production. If the price of oil rises, this cut-off rate will fall and so more oil will be recovered from the field. This will increase the URR, manifesting as reserve growth. The effect of such a price increase on reserve growth is hard to estimate however, as it not only depends on the extent of the oil price rise, but also, since cut-off rates will vary from one field to another, on the characteristics of each individual field.

One method to examine the second of the above effects, previously uneconomic fields being brought on line, is to examine the number of fields that have been discovered but not developed and determine a reasonable percentage of these that might come on line if the oil price rose sufficiently.

Conversely however, any discovered but undeveloped fields that have been included in a reserve or discovery database that will either never be commercially viable, or which will cease to be commercially viable if the oil price drops will need to be removed. For example, if the oil price dropped significantly below the cost to produce Canadian oil sands, these would no longer be seen to be producible and, according to the McKelvery box, would change from reserves to resources, resulting in reserve shrinkage.

The extent of potential reserve growth or shrinkage by this mechanism will depend on how IHS assesses fields and includes them in its database. It seems likely that when a field is discovered, it would decide or determine whether it is likely to be economical or not and hence whether to include it as a discovery or not. If a field is not incorporated into the database when it is discovered, it could potentially be developed regardless of the IHS classification in which case it could appear as reserve growth. On the other hand, if it is counted as discovered and if crude oil prices fell sufficiently, it might need to be removed. The possibility of reserve shrinkage on this basis is also mentioned by Chew (2007), who indicated that one potential downsizing of the IHS database will come from some stranded accumulations not being developed.

In 2008 the IEA (2008, page 257) reported that there were 257Gb of discovered undeveloped oil fields throughout the world, while Meling (2003) reported that in 2002 there were 200Gb. Unfortunately neither of these were split into economical/uneconomical fields and no mention is made of whether, and if so how, IHS had included them in its database.

Based on a BP review of IHS's database, Bentley et al. (2009) estimated that there were roughly about 150Gb fields which had been included in the IHS 2P reserve database that were likely never to become economic to develop. A very different number is given by IHS (Wade, 2007), which reported in a presentation, that in 2007 there were only around 145Gb of discovered undeveloped oil fields throughout the world, of which 73% would become commerically viable with oil prices of $40 and above. This implies that there were only around 40Gb resources that would not be viable at $40. This is significantly lower than Bentley's figure, and when coupled with the recent oil prices much greater than $40, as well as the possibility that only a part, or indeed none, of these might have been included by IHS in its 2P reserve database (meaning that they would not necessarily manifest as reserve shrinkage) it is likely to be even smaller.

It seems likely that increasing oil prices will have the greatest effect on the production of deepwater, ultra deepwater and arctic oil fields. According to the IEA (2008), these have higher costs than other forms of conventional oil and so they are likely to be exploited only with higher production revenues. Campbell and Heapes (2009) report that there are around 70Gb oil in deep offshore areas, which given a high enough price, could therefore be brought into production.

3.3 Analysis of reserve growth experienced and predicted

The difficulties in predicting by how much each of the components will grow or shrink in the future are obvious from the previous sections, but there are nevertheless a number of sources that attempt to predict remaining global reserve growth and it is useful to compare their estimates. Before doing so, however, and in order to develop a method for properly examining these sources, it is useful to look at estimates of reserve growth that have already occurred.

3.3.1 Reserve growth experienced

Klett et al. (2007) analysed the volumes of reserve growth forecast in the USGS 2000 World Petroleum Assessment. This showed that at the end of 2003, i.e. after 27% of the full 1995 - 2025 time frame of the assessment, 171 Gb of reserve growth in crude oil had occurred throughout the world outside US and Canada. Thompson et al. (2008) state that the estimate is therefore in *'excellent agreement with the forecast'* as 28% of the mean USGS estimate for global (excluding the US) reserve growth of 612Gb had been realised. These figures are not directly comparable however due to the inclusion of Canada in the USGS global (excluding the US) reserve growth figure of 612Gb and in order to compare them correctly, an estimate of how much Canadan reserve growth might be expected should have been made and removed from the global figure.

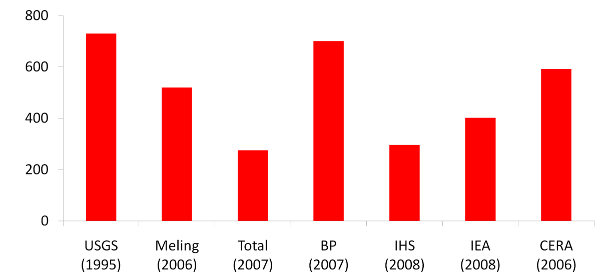
Nevertheless, Stark and Chew (2005) indicate a similar figure of 175Gb 'classic' reserve growth between the end of 1994 and 2003. Although this appears to include US and Canada, is for a longer timeframe, and includes all liquids while Klett et al. (2007) included only crude oil, Bentley et al. (2007) indicate that Chew had stated that his reserve growth figures were only a *'reasonable ball-park estimate'* and so this figure shows relatively good agreement with the USGS figure.

Chew and Stark (2006) also indicated in a presentation that there was only 9Gb of reserve growth in 2005. Although this is likely to include both 'reporting' and 'classic' growth, it is still less than half the annual average of 'classic' reserve growth ($\sim$20Gb/year) that their previous report suggested had occurred annually between 1994 and 2003. On the other hand, Thompson et al. (2008) analyse reserve growth between 2000 and 2007 using 2P reserve estimates and conclude that the rate of non-US reserve growth has actually increased in recent years up to $\sim$33Gb/year. It is unclear whether they are referring solely to classic reserve growth and have taken any account of identifying and removing any 'reporting' reserves growth that may have occurred between 2000 and 2007, but these results show that estimating the amount of reserve growth that has occurred, even with suitable data, is an uncertain task.

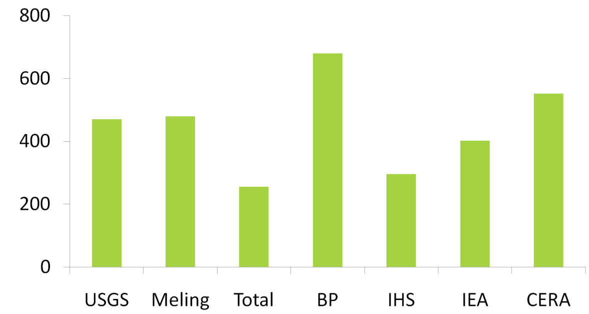
3.3.2 Reserve growth predicted

As mentioned, numerous predictions of future reserve growth have been made. These were obviously not all produced in the same year with projections for the same periods and so in order to compare them properly they need to be slightly modified. As mentioned in the previous section, the numbers of Stark and Chew (2005) can be used to estimate that there has been linear yearly rate of reserve growth of $\sim$ 20Gb/year. This can therefore be used to 'project' estimates up to the base year, taken here to be year-end 2008, even if they were produced some years before. For example, the USGS forecast period started at the end of 1995 and so a total of $(2008 - 1995) \times 20$ Gb needs to be subtracted from the crude oil and NGL combined global (this including the US) 730Gb reserve growth predicted. This leaves a total of 470Gb of the USGS mean reserve growth estimate remaining from 2008 to 2025.

As shown above, estimates of reserve growth that have occurred vary significantly, and so the assumption



(a) Reserve growth predicted by the sources identified. Numbers in brackets are the relevant year-ends for each prediction



(b) Reserve growth from 2008 under the assumption that 20Gb/year reserve growth has been experienced each year from the date the prediction was made

Figure 8: BP's prediction is for maximum reserve growth. The estimate of Total only includes EOR that it indicates will increase the recovery factor of the oil in place (stated to be 5500Gb) by 5%. The CERA estimate is also only the figure it indicates for EOR and, although it identifies other sources increasing global URR such as deepwater and arctic oil, these have not been included. Both Total and CERA make no other mention of the other contributory factors mentioned in §3.2 above

Sources: USGS (Ahlbrandt et al., 2000); IHS (Stark, 2009); IEA (2008); Bentley et al. (2009); CERA (2006)

of $\sim$ 20Gb reserve growth per year is highly questionable.[12] Nevertheless, the $\sim$ 20Gb/year figure has been employed because it has been derived from the most complete data set available (the 9Gb suggested by Chew and Stark (2006) could have been an anomalous year), and does provide a rough but transparent method of comparing reserve growth estimates.

One can therefore directly compare each of the estimates of remaining reserve growth. These are presented in Figure 8. Figure 8(a) displays the raw, unmodified estimates in the years that the predictions were made, while Figure 8(b) presents the data modified to a base year of 2008.

It is assumed that all of the sources report reserve growth in conventional oil only. IHS could include some unconventional oil reserve growth as it mixes the two in its 2P reserve database but this seems unlikely, as when discussing the subject in a later presentation, Stark (2009) from IHS considered reserve growth and unconventional oil separately.

Sources to be preferred when assessing the contribution of reserve growth to global remaining resources are those consider as many of the above factors contributing to reserve growth as feasible and that do not rely upon reserve growth functions. USGS used a reserve growth function, CERA and Total only considered EOR and, unfortunately, Bentley et al. (2009) do not reveal how the reserve growth figures for Meling and BP were determined. It is also unclear how IHS has derived its estimate. The approach by IEA, although

[12]Klett et al. (2005) also suggest that the reserve growth experienced between 1995 and 2003 may have been amplified by a preference of developers to invest in increasing the recovery factor in existing fields rather than undertaking more risky and higher cost exploration for new fields.

it does not indicate precisely how it formed its 402Gb estimate, does mentions economic, technological and geological changes when referring to reserve growth and it is therefore likely to be the most useful source. It also appears that it has not been derived simply by increasing the recovery factor by a certain percentage given that it had previously quoted in IEA (2005a) that the recovery factor could be increased by 10% giving a potential 800Gb contribution. The other estimates, with the exception of USGS, do nevertheless also provide useful bounds.

There are undoubtedly large uncertainties in the global reserve growth figure and any methodology for apportioning reserve growth to individual countries is therefore likely to contain even larger errors. Nevertheless, in order to determine estimates of individual countries' remaining reserve growth, this is a necessary step to take. The following methodology can be used to do so.

The USGS attached data tables to its 2000 assessment, and two of these, 'kdisc.tab' and 'gdisc.tab' (standing for 'known discovered' and 'grown discovered') give respective 2P estimates of oil in assessment units (AU)[13] before and after application of a number of different reserve growth algorithms according to Klett of USGS (priv.communication). The amount of reserve growth estimated for each AU can therefore be calculated by subtracting the figures in kdisc.tab from gdisc.tab. The sum of reserve growth calculated by this method in every AU is ∼400Gb, which is obviously significantly different from the USGS stated value of 612Gb mentioned above. Klett (priv.communication) explained that this discrepancy arises because these tables were only used to aid estimation of the amount of undiscovered oil in each AU and not to assess global reserve growth, for which the US 1P reserve growth function was used.

This subtraction of figures in kdisc.tab from gdisc.tab does however give a first estimation of the amount of reserve growth that will be experienced in every AU. The reserve growth in AUs in each country (or those that can be assigned to that country) can therefore be isolated.[14] The total figure of 400Gb derived by this method can then be increased pro-rata to the most 'correct' global figure of 402Gb given by IEA.

4 Undiscovered resources

Yet-to-find or undiscovered resources can be defined as resources that are *'postulated from geologic information and theory to exist outside of known [or discovered] oil and gas fields.'*(Ahlbrandt et al., 2000).

To date there have been five USGS periodic assessments of global URR and undiscovered resources, with the latest in 2000, but updates for a number of individual countries or areas outside US have been released

[13]An AU is an area of rock that *'shares similar geologic traits and socio-economic factors.'* outside the US (Ahlbrandt et al., 2000). USGS studied 246 assessment units in its 2000 World Petroleum Assessment that it considered might hold conventional oil or gas.

[14]If an AU crosses a border, the reserve growth expected in it can be assigned partly to each relevant country using the table sum_ca.tab which identifies how the USGS assigned AUs to countries in its assessment.

since this date, for example, Brownfield et al. (2010) on West Africa. The USGS assessments are the most comprehensive and frequently quoted sources when analysing undiscovered resources (Sorrell et al., 2009).

As mentioned above, in its 2000 assessment, the USGS quantitatively assessed a total of 246 assessment units. The procedure to determine undiscovered resources for an individual AU is described by Ahlbrandt et al. (2000), and involved a combination of geological assessments and discovery process modelling.

Similar to its approach for reserve growth, the USGS assumed current technological and economic conditions within its timeframe of 1995 - 2025 i.e. the figures it gives represent the amount of oil or gas that have the potential to be discovered in the thirty year period from 1995. As noted above at §3.3 however, Ahlbrant indicates that these should not be interpreted too literally and IHS views them as the ultimate that will be discovered.

There is considerable debate surrounding the USGS estimates of undiscovered resources. Numerous authors, including Laherrere (2000) and Schindler and Zitell (2008) attacked the USGS figures as being too optimistic about future discoveries, while others such as Skrebowski (2006) indicate that the USGS mean estimates were *'spot on'*. Laherrere (2000) also indicates that the USGS use of 'growing' reserves in undiscovered fields was erroneous, as *'in practice the reserve estimates made prior to the drilling of a prospect are almost always much higher than those initially attributed to the discovery if it is success[ful]'*.

The Chew and Stark (2006) presentation mentioned above also provides information on the volume of discoveries between 1995 and 2005 in each USGS region[15] and indicates that global discoveries totaled 133Gb in the 10 year period. EWG (Schindler and Zitell, 2008) gives a similar figure of around 140Gb for the same period.

Figure 9 compares global undiscovered estimates from various sources. The majority of these unfortunately do not provide disaggregate tables but they can be used to indicate the range of estimates of global undiscovered resources that exist. In a similar method to that used for reserve growth, estimates for all sources other than USGS (see below) can be increased to a base year of 2008, as presented in Figure 9(b) by adding or subtracting the aggregate global discovery rate of 13Gb/year derived using the figures in the previous paragraph. Again this linear discovery rate is highly questionable but Bentley et al. (2009) report that the BP model uses a discovery rate of 10Gb/year that it describes as *'sustainable'*. [16] This indicates that a linear discovery rate is also used by other analysts. I prefer the figure of 13Gb/year however as it is not clear how BP arrived at its figures of 10-20Gb/year. Estimates are again assumed to be the ultimate recoverable.

[15]The presentation provides these estimates as a percentage of the USGS estimate but these can be easily converted to absolute discoveries.

[16]It also reports that that this could be increased to 20Gb discovered every year for the next 15 to 20 years under certain circumstances.

As mentioned above, the USGS occasionally releases updates of undiscovered oil and NGL for various countries or regions. There have been a total of 20 of these regional papers between 2003 (for West Siberia) and 2010 (for the Nile Delta region) that have either updated undiscovered oil in AUs that were assessed in the 2000 World Petroleum Assessment or provided information on new AUs that were not previously examined. In order to assess the amount of undiscovered resources throughout the world, the 2000 USGS assessment therefore needs to be updated to reflect these reports and to account for any discoveries that have happened. The following methodology was therefore employed:

1. Data table sum_au.tab provides mean undiscovered resources in all AUs assessed in the 2000 World Petroleum Assessment. Update this table to account for the new information in the 20 papers by updating mean undiscovered oil in AUs that have been modified and incorporating any AUs that were not previously assessed;

2. Use Chew and Stark (2006), which gives the percentage of the USGS original estimate discovered between 1995 and 2005 in each region, to determine a percentage of undiscovered oil discovered/year in each region;

3. Using the USGS assignment of countries to regions and table sum_ca.tab, which allocates AUs to countries, determine which AU is in which region.

4. Assume that the above percentage of undiscovered oil discovered/year in each region corresponds to a percentage of undiscovered oil in each AU discovered/year;

5. If an AU has not changed, subtract 13× the percentage of undiscovered oil in that AU discovered/year (for the thirteen years from 1995 and the base year of 2008) from the original amount, to give remaining undiscovered resources in that AU;

6. If a previously assessed AU has been updated, subtract or add[17] the percentage (of the original 2000 USGS Assessment estimate of undiscovered oil in that AU.)[18] discovered/year for each year between the year it was updated and 2008;

7. For new AUs, assume that the relevant percentage discovered/year has been made from the year the update was given and subtract this from the mean AU undiscovered volume;

[17] Those AUs that were updated after the end of 2008 need to have a percentage of discoveries added to reflect the amount of undiscovered oil that would have been present 2008

[18] The IHS presentation refers to the original volume of oil estimated by USGS that has been discovered and not any updated estimates. Any percentage discoveries should therefore be applied to the original amount even if subtracted from the updated estimate.

8. Re-assign the AUs back to countries as in sum_ca.tab. For new AUs, assign these to countries on an area basis (this is a simplification of the original USGS procedure as detailed in Ahlbrandt et al. (2000, chpt. AA) but relatively few AUs are affected by this as most are already assigned in sum_ca.tab or lie wholly within countries);

9. For the US, which did not form part of the 2000 assessment, the undiscovered conventional oil is 48.76Gb for onshore regions and 85.88Gb in offshore continental regions(USGS, 2008; Service, 2006).

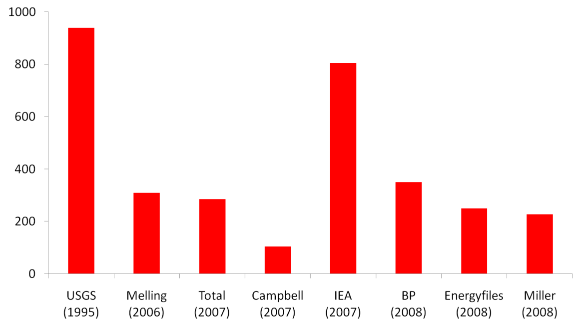
Since Chew and Stark (2006) provided discoveries in each USGS region, an absolute global discovery/year did not need to be used. Assignment of AUs to the relevant regions and use of the regional discovery/year therefore increases the resolution and accuracy of the procedure.

For example, assume that an AU in Africa, that was originally estimated to hold a mean undiscovered oil volume of 10Gb was updated in 2005 with a new estimate of 15Gb. Firstly, according to Chew and Stark (2006), this African AU would have 3.24% of the undiscovered oil it holds discovered every year. With the three years between 2005 and 2008, we would expect 9.72% ($3 \times 3.24\%$) of undiscovered oil to have been discovered. 9.72% $\times$ the original amount of 10Gb = 0.972Gb, means that the AU is estimated to hold 15Gb $-$ 0.972Gb = 14.03Gb $\sim$ 14Gb in 2008. This volume would then be reassigned to the relevant country(ies).

This methodology results in a modified and updated country by county database for undiscovered conventional oil, which is presented in Figure 9(b). This volume has increased slightly between 1995 and 2008, despite ongoing discoveries throughout the thirteen years. This arises predominantly from an increase of over 51Gb in estimated US undiscovered resources, from a major reassessment of AUs in West Africa, and from the inclusion of assessment units in the Arctic Circle adding around 35Gb of discovered resources.

The USGS and IEA figures can be seen to be considerably higher than the other estimates (IEA has in part relied upon the USGS 2000 World Petroleum Assessment as well as its own databases) which can be explained to some degree by the inclusion of resources found in arctic and ultra-deepwater areas by the USGS, areas excluded by a number of the other sources. Arctic areas, for example, are estimated to include about 130Gb undiscovered oil.

The updated USGS database therefore offers a high end estimate of undiscovered resources while Campbell, who also provides information at a disaggregate level, offers a lower bound. The remaining five sources are relatively consistent and predict a global undiscovered estimate of $\sim$ 280Gb$\pm$50Gb with the plus-or-minus figure indicating the one standard deviation error. This result is a little surprising as BP and Energyfiles indicate that their figures include unconventional liquids and unconventional oil respectively, while the other sources include only conventional oil. This suggests that the contribution of undiscovered unconventional



(a) Undiscovered resources predicted by various sources. Numbers in brackets are the relevant year-ends for each prediction

(b) Undiscovered resources from 2008 using the assumption that $\sim$ 13Gb/year have been discovered each year from the date the prediction was made, except USGS figure, which was determined using the methodology in the main body of text.

Figure 9: Estimates indicated are for conventional oil as defined by the individual sources and include NGL where separated. Total's and BP's figures are the averages of the 200-370Gb and 300-400Gb (respectively) ranges specified

Sources: USGS (Ahlbrandt et al., 2000); IHS (Stark, 2009; Chew and Stark, 2006); IEA (2008); Campbell and Heapes (2009); Bentley et al. (2009)

liquids to undiscovered oil is expected to be small.

These estimates are unfortunately not available at a country-level resolution. If we wanted to examine the undiscovered resources of countries using this median estimate, one potential method, albeit quite inaccurate, would be to pro-rata the country estimates provided by USGS (excluding the arctic regions which can be easily isolated) to this global figure of 280Gb.

There is one further database produced by BGR (2009), which includes *'the remaining resources that are either proved but at present not economically recoverable, or not demonstrated, but can be expected for geological reasons'*. It is not clear from its reports what is included in its remaining resources as some aspect of reserve growth and not just undiscovered resources could be included. Nevertheless, its contribution is useful for comparison once an estimation of undiscovered resources is combined with an estimate of global reserve growth.

To this end, on a global scale, the BGR estimate of 664Gb compares well to our 'best guess' estimates consisting of the IEA estimate of reserve growth of around 400Gb and the average of the five sources mentioned above giving undiscovered resources of around 280Gb. The apparent correlation between these results is encouraging but it should not be forgotten that there is a huge range of uncertainty in both the reserve growth and undiscovered resources figures. It is also possible to roughly compare the BGR estimates with reserve growth plus undiscovered resources on a country level if the pro-rata method of apportionment is employed, which again produces a good corrleation.

5 Conclusions

The list below summarises the principle conclusions of this paper and the key uncertainties in estimating the remaining recoverable resources of conventional oil:

- reporting sources include different subcategories of oil in their reserve estimates, report oil using variable and inconsistent definitions of conventional oil, reserves and resources, and do not properly analyse or assess the reserves reported, making comparison of estimates difficult;
- political reserves are often included in 1P reserve estimates meaning that these are unsuitable for any rigorous analysis;
- the number of 2P country level databases that are available are limited although these do provide valuable information;
- the effects of aggregation of field-level 2P reserve data to country and regional estimates are inconsistent and unclear;
- non-zero future reserve growth is anticipated, but the nature and extent of this is difficult to determine. This arises from the numerous effects that could add or detract to it, comprising definitional factors, enhanced oil recovery, better understanding of reservoir geology, and oil prices, all of which contain numerous uncertainties themselves. Sources predicting future reserve growth need to address all of these issues, but few do so. Nevertheless, an estimate of future global reserve growth (not relying upon the use of reserve growth functions, whose use is inappropriate) can be used to allocate future reserve growth to countries;
- there are a wide range of estimates of undiscovered oil, and although this range results partly from the inclusion by some sources of oil in difficult to access areas, the most comprehensive and wide-ranging database produced by USGS differs significantly from other contemporaneous estimates. This can be used, however, to apportion other estimates of undiscovered oil to countries; and
- it is therefore possible estimate the remaining recoverable resources of conventional oil held by individual countries although only with large errors.

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