Unconventional Gas – A review of estimates

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Abstract

The future potential for unconventional gas production remains contentious, with questions over the size and recoverability of the physical resource being central to the debate. While interest has focused upon shale gas in recent years, there is also considerable potential for coal bed methane (CBM) and tight gas to contribute to global gas supply. However, despite recent advances there remains considerable uncertainty over the size of recoverable resources for each type of gas, at both the regional and global level. This even applies to the United States, where the development of shale gas resources is relatively advanced. This paper summarises and critically evaluates the regional and global estimates of CBM, tight gas, and shale gas resources and compares these with current estimates of conventional gas resources.

The paper identifies a total of 69 studies providing original country-level estimates of unconventional gas resources, with 49 of these (70%) being published since the beginning of 2007. These estimates have been derived using a variety of methods and are presented in a variety of ways, which makes comparison between them very difficult. Hence the paper first explores the meaning and appropriate interpretation of the various terms and definitions that are currently employed, focussing in particular on the influential estimates provided by the United States Geological Survey ('USGS'). It then presents the different regional and global resource estimates that have been produced, shows how these have increased over time, compares the results, highlights the variability in these results and the inadequate treatment of uncertainty and summarises the overall implications.

1. Introduction

In recent years natural gas and its use as a primary energy vector has enjoyed increasing attention. This has largely been driven by two factors: 1) the increasing belief that natural gas will be abundant and cheap in the future, including increased exploitation of unconventional gas; and 2) the resulting rhetoric that gas will facilitate the transition to a decarbonised economy through its use in electricity generation, domestic heating, and as a transport fuel with relative carbon benefits.

This developing gas paradigm reinforces the importance of establishing an evidence base around which claims of future gas abundance can be supported or rejected. A key component of this evidence base must be the estimation of existing resources. In this paper we review the available evidence on the size of the global natural gas resource, report the findings of that evidence, and draw conclusions as to the robustness of that evidence and its implications for estimation of future unconventional gas availability.

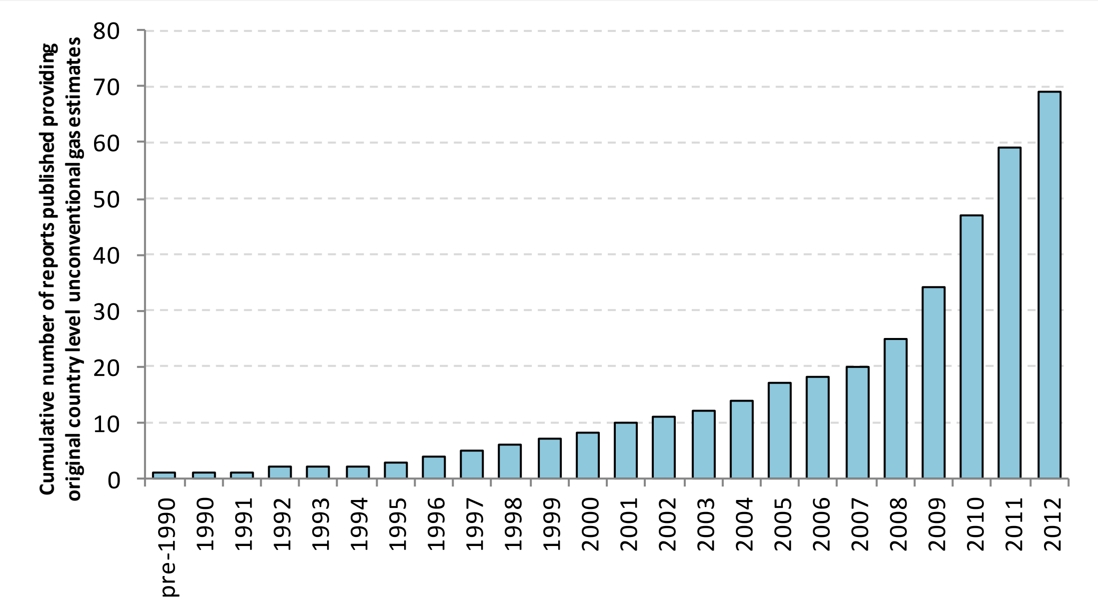
We consider unconventional gas to include shale gas, tight gas and coal bed methane (CBM) and include estimates of the resources of all three where possible. Further discussion of the classification of unconventional gases can be found in Section 2. The definition of 'unconventional' is either based on the technology needed to extract the gas or some absolute measure of the permeability of the source rock. These two approaches create a level of ambiguity and as a result some reports consider tight gas to be 'conventional.'

We only include resource estimates which we consider original, meaning any estimate which is developed by the author using a recognised methodology or adapted by explicitly altering an existing estimate. Three methodologies are typically used to estimate unconventional gas resources: Literature review/adaptation of existing literature; bottom up assessment of geological parameters; and extrapolation of historical production experience.

As can be seen in Figure 1 there are 69 reports providing original country-level estimates of unconventional gas resources, with 49 of these (~70%) published since the beginning of 2007. The primary motivation for these studies has been the rapid development of US shale gas resources, with 56 of the 69 reports providing resource estimates for the United States and/or Canada.

In Section 2 we discus existing resource definitions and their implications for unconventional gas. In Section 3 we present the estimates found in the literature. In Section 4 we present these estimates in the context of conventional gas resources before presenting conclusions in Section 5.

Figure 1: Cumulative number of reports published providing original country level estimates of any of the unconventional gases



2. Resource definitions

Unconventional gas resources may be estimated for given spatial scales and may refer to volumes of gas that are estimated to be present or producible either technically or economically. These estimates may be presented probabilistically or to a given level of confidence (e.g. 'probable' or 'possible'). Clearly defining these, and explicitly stating to which estimates these definitions apply is fundamentally important as confusion and inaccuracy frequently occur when estimates using different definitions are compared.

Resource definitions also suffer from inconsistent or ambiguous use. For example, the term 'undiscovered' is used for conventional oil and gas resources to refer to oil or gas *'Resources postulated from geologic information and theory to exist outside of known oil and gas fields'* [1]. In unconventional gas the location of the gas is usually known, though the detailed nature of the geology and the total recoverable volume of gas may be entirely unknown. These resources are still referred to as 'undiscovered' by many sources however.

There are also varying definitions of 'undiscovered' increasing ambiguity. The Society of Petroleum Engineers (SPE) Petroleum Resources Management System (PRMS) for example indicates that 'discovered' shale gas resources require *'collected data [that] establish [es] the existence of a significant quantity of potentially moveable hydrocarbons.'* [2]. However it does not allow one to distinguish between resources classified as undiscovered under the definition given by [1], and resources in areas that are known but do not meet the above requirement. Unless otherwise stated, the term 'undiscovered' in this report refers only to the traditional definition - i.e. gas that is estimated to exist outside of known formations.

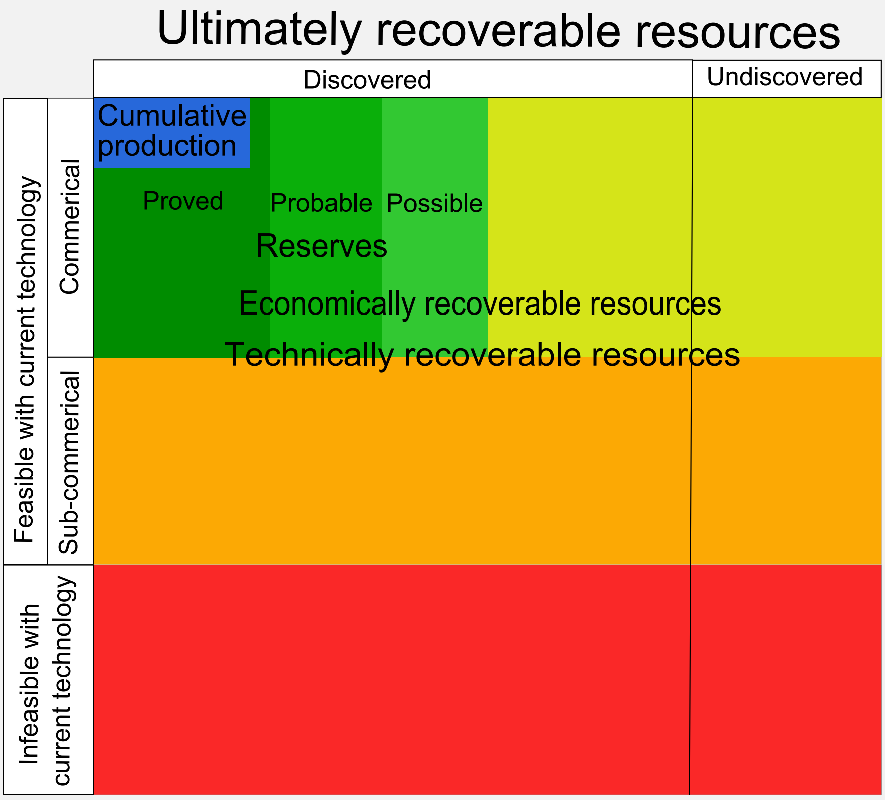
There is only one source explicitly reporting 'undiscovered' using this definition – INTEK [3] , which indicated 1.2 trillion cubic meters (Tcm) in Southern California and 0.4 Tcm in the Rocky Mountain region which had been *`estimated by the USGS'*. We have been unable to located provenance of these figures however despite communication with the USGS, and regardless, as discussed below, the USGS provides *'potential additions to reserves'* and not 'undiscovered' resources in this sense. It is therefore not clear that this number was correctly interpreted by INTEK. As a result, it appears that no explicit estimates of undiscovered shale gas (estimated to exist outside of known formations) have been made for any region.

There are four key terms used to define volumetric unconventional gas resource estimates, and a fifth set of definitions which define the specific probabilities of reserve estimates. These are summarised in Table 1 and the Mckelvey box in Figure 2: McKelvey box of resource classifications for unconventional gas. We describe these terms below in order of decreasing inclusivity.

Table 1: Brief descriptions of resource and reserves for natural gas used in this report

Name	Short description	Includes gas in un-discovered formations	Includes gas not economically recoverable with current technology	Includes gas that is not recoverable with current technology	Includes gas that is not expected to become recoverable
Original gas in place	Total volume present	✓	✓	✓	✓
Ultimately recoverable resources	Total volume recoverable over all time	✓	✓	✓	
Technically recoverable resources	Recoverable with current technology	✓	✓		
Economically recoverable resources	Economically recoverable with current technology	✓			
1P/2P/3P reserves	Specific probability of being produced				

Figure 2: McKelvey box of resource classifications for unconventional gas



Original Gas In Place (OGIP) is the total volume of natural gas that is estimated to be present in a given field, play or region. This volume is never 100% recoverable, with the fraction of this gas that can be recovered referred to as the *recovery factor*. This is a key factor in estimating gas availability and can vary significantly depending of geological conditions, technologies used, and the prevailing economic environment.

Ultimately Recoverable Resources (URR) is the sum of all gas expected to be produced for a field or region over all time. This estimate therefore includes not only gas already produced, and gas resources already discovered, but gas which is not currently producible either technically or economically but is expected to be so in the future, and undiscovered gas (using both of the above interpretations) which is expected to be discovered in the future. This definition is therefore sensitive to a range of assumption about future gas prices, future technological developments, and future discovery rates. URR is closely related to *Estimated Ultimate Recovery (EUR)* which is commonly used to refer to a single well but for all other purposes is synonymous.

Technically Recoverable Resources (TRR) is the gas producible with current technology, but excluding economic constraints. However, there is some ambiguity as to whether this classification includes undiscovered gas, with contradictory statements appearing in some reports. For example the EIA suggest in one document both that undiscovered resources are excluded and included. However the majority of evidence suggests that undiscovered gas should be included. We consider TRR to include all variations of undiscovered resources discussed above. Not all literature explicitly identifies whether cumulative production is included or not. Another definition, *Remaining Technically Recoverable resources (RTRR)*, can be used to explicitly exclude cumulative production.

Economically Recoverable Resources (ERR) is a subset of TRR and defines the technically *and* economically producible gas given current technical and economic conditions. As such this definition is sensitive to changes in economic conditions. It is questionable whether or not undiscovered resources should be included in estimates of ERR and it is difficult to defend the basis for any assumptions on the economic producibility of gas resources which have not been found. However, some reports do include some form of undiscovered resources [4-8] and to maintain consistency with conventional estimates we also include all variations of undiscovered resources in our definition of ERR.

Then there are the probabilistic *Reserve* definitions. There are three separate definitions, each with a specific probability. *1P or Proved* is sometimes referred to as P90 and represents an estimate with a 90% probability of being exceeded. *2P or Proved and Probable* is sometimes referred to as P50 and represents an estimate with a 50% chance of being exceeded (the median estimate). *3P or Proved, Probable and Possible* is sometimes referred to as P10 and represents an estimate with a 10% chance of being exceeded.

There are two problems associated with these classifications. First, it is unclear whether estimates given using these definitions correspond to these precise statistical definitions. There is little ex-post analysis of field or region production performance to support the perceived accuracy of these estimates. Second, the aggregating of probabilistic estimates can be problematic. Statistically, it is only valid to arithmetically sum reserve estimates if these correspond to *mean* estimates of recoverable resources. If instead 1P (P90) reserve estimates are arithmetically summed, the aggregate figure will *underestimate* total reserves. Similarly, if 3P (P10) reserve estimates are arithmetically summed, the aggregate figure will *overestimate* total reserves [9, 10]. Aggregation of 2P reserve estimates should lead to smaller errors, but the magnitude and sign of these errors will depend upon the difference between *mean* and *median* estimates and hence the precise shape of the underlying probability distribution (which is rarely available). In practice, aggregation of 1P estimates is more common, thereby leading to underestimation of regional reserves.

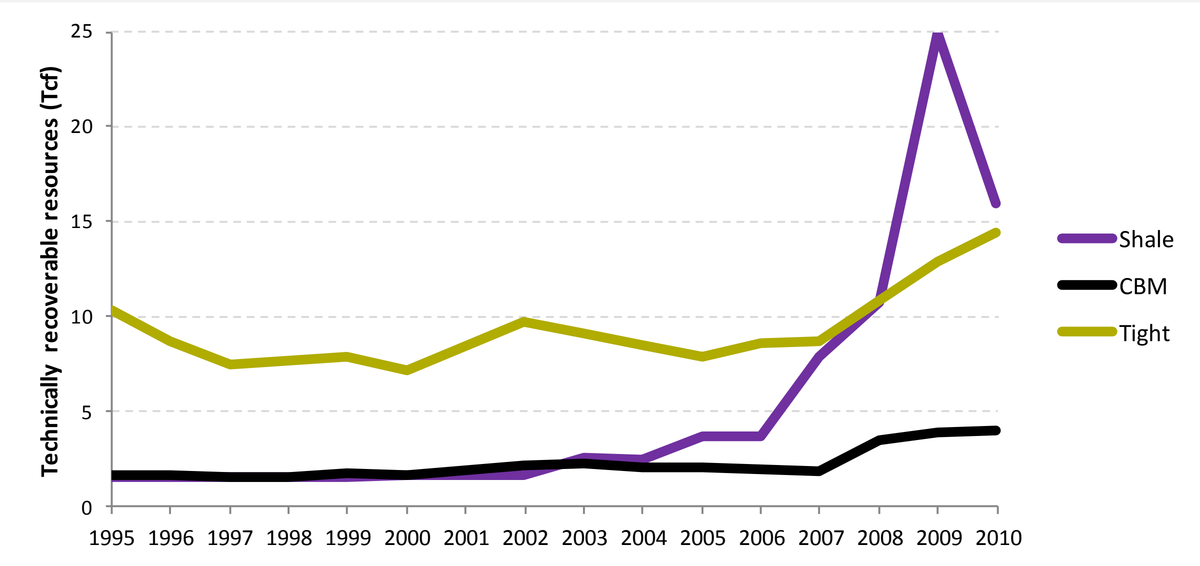
Finally there are exceptions to the neat classification discussed above. It is important to examine the USGS definitions since they are influential regular publishers of data and are entirely unusual and ambiguous. USGS estimates a separate resource class termed *potential additions to reserves,* which through direct contact with authors has been identified as TRR minus undiscovered, minus existing reserves and minus cumulative production. Therefore it is important to add existing reserves, cumulative production, and some estimate of undiscovered to the USGS figure to create comparability with TRR estimates for other authors. This must be done while avoiding the problems associated with addition of probabilistic estimates discussed above. A best-practice approach is to add proved reserves and inferred reserves (considered by the EIA to be analogous to probable reserves [11]) to create a 2P estimate, which can then be summed across all fields/regions of interest. This can then be added to estimates of cumulative production and undiscovered resources.

In summary, the use of resource definitions is inconsistent, imprecise and in need of standardisation. It is most important when reporting reserve and resource data to be explicit about resource definitions. TRR is probably the most useful resource definition because it is used most often and gives ability to compare studies. ERR is useful in the short term, but given the likely variability of price, it is unlikely to give a useful estimate over time. URR would be the best type of estimate to use since it should incorporate the variability in assumptions over time. But it is unlikely to become widely available given the difficulty in capturing that variability. Given the early stage of production of this resource and the very large uncertainty in all resource estimates, we may anticipate considerable overlap between URR, TRR and ERR estimates - despite the conceptual distinction between them.

3. Estimates of unconventional gas

Few studies provide estimates for all three types of unconventional gas, with the majority focusing on shale gas. One exception is the EIA whose Annual Energy Outlook (AEO) has provided RTRR for all unconventional gases in the US since 1997 (publication in 1997 earliest estimate for 1995). Figure 3 shows the growth in estimates between 1995 and 2010 for all three gases: tight gas increased 40%, CBM increased 138%; while shale gas increased by a factor of 9 (though before the recent tail-off estimates had increased by a factor of 15).

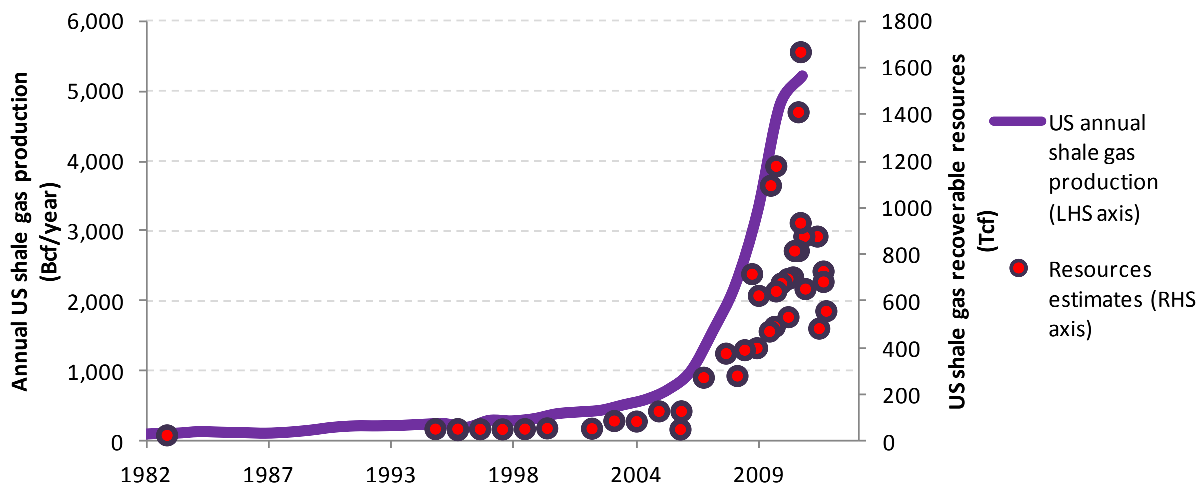
Figure 3: Estimates of remaining recoverable resources for unconventional gases in the United States in successive Annual Energy Outlooks from the US Energy Information Administration



Source: **EIA [12]. The 1998 and 1997 AEOs provided estimates of remaining ERR while all others provided estimates of remaining TRR.**

For existing estimates there is significant variation. This is demonstrated for the US where estimates of shale gas resources have increased significantly in the last 6 years (see Figure 4).

Figure 4: US shale gas resource estimates and annual production



Source: **Production data from 1982- 1989 taken from Slutz [13]; data from 1990 onwards taken from EIA AEO 2011. Graph includes both TRR and ERR resource estimates from all sources. The USGS figure combines all of its latest resource assessments for shale plays of various dates but is plotted at August 2011, the date of the most recent USGS assessment of the Paradox basin[14]**

We now discuss the existing estimates in more detail, first shale gas, where a significant proportion of the evidence lies, followed by tight gas and CBM.

Estimates of shale gas

Shale gas is the most topical of the unconventional gases currently and as a result a large proportion of the evidence addresses this gas type. First we examine global estimates of shale gas resources before focusing on North America, Europe and China. Other regions are not covered in sufficient detail for comparison and this is a fundamental weakness in the literature. It is important to note that, while the potential for offshore resources is an on-going debate [15], only one estimate for offshore shale gas resources exists. That estimate is for Poland [16], and is relatively small compared to onshore estimates (0.11-0.15 Tcm compared to onshore of 0.23-0.62 Tcm).

We identify 62 sources that provide original country or region level estimates of shale gas (the most recent of which are presented in Table 2). It is not always stated whether these studies include undiscovered resources, though this could be assumed by examining whether they identify specific plays and/or suggest the potential for discovery outside these plays. As discussed above, although INTEK [3] estimate that there is 1.6 Tcm of undiscovered shale gas in the United States, this is unlikely to actually correspond to undiscovered gas in the traditional sense. For this reason, unless estimates have implicitly included some estimate of undiscovered shale gas and not stated this, all estimates of *'discovered TRR'* will be identical to estimates of *'full TRR'*.

Table 2: Shale gas reports providing original country level estimates by date, countries or regions covered and type of resource estimate since 2009

Author/organisation	Date of report	Countries/regions covered	Resource estimate
EIA (AEO)[17]	Various[1]	US	TRR (2012 – 1999) ERR (1998 & 1997)
Dai [18]	Jun-12	China	TRR
Medlock *et al.* [19]	May-12	29 countries	TRR and ERR
BGR [20]	May-12	Germany	OGIP and TRR
Jia *et al. [21]*	Apr-12	China	TRR
Chinese Ministry of Land Resources [22]	Mar-12	China	TRR
PGI [16]	Mar-12	Poland	TRR
USGS[2]	Mar-12	US	Potential to be added to reserves'
BGR [23]	Feb-12	Top 15 countries and other regions	TRR
PEMEX [24]	Jan-12	Mexico	'Prospective resources'
USGS[25]	Jan-12	India	'Potential to be added to reserves'
Mohr & Evans[26]	Sep-11	Continental regions	URR
USGS[27]	Aug-11	Uruguay	Potential to be added to reserves'
Medlock *et al.*[28]	Jul-11	9 North American, European and Pacific countries	TRR[3]
INTEK (for EIA)[3]	Jul-11	US	'Unproved, undiscovered TRR'[4]
ICF (Petak)[29]	May-11	US. Canada	ERR[5]
Advanced Resources International (Kuuskraa)[30]	May-11	US	TRR
ARI (for EIA) [31]	Apr-11	32 individual countries worldwide	OGIP and TRR
ICF (Henning)[32]	Mar-11	US, Canada	ERR[4]
ARI (Kuuskraa)[33]	Jan-11	US	TRR
Potential Gas Committee [34]	Dec-10	US	TRR
Caineng *et al.*[35]	Dec-10	China	OGIP
Medlock & Hartley[36]	Oct-10	US, Canada	TRR
ARI (Kuuskraa)[37]	Oct-10	US	TRR
World Energy Council[38]	Sep-10	9 Continental regions	OGIP
Mohr & Evans [39]	Jul-10	US, Canada	URR
MIT (Moniz)[40]	Jun-10	US	TRR
CSUR (Dawson)[41]	May-10	Canada	ERR
Skipper[42]	Mar-10	US, Canada	TRR
Hennings[43]	Mar-10	US	OGIP and TRR
ARI (Kuuskraa)[44]	Mar-10	US, Canada	TRR
Petrel Robertson Consulting[45]	Mar-10	Canada	OGIP
IHS CERA (Downey)[46]	Jan-10	US, Canada	TRR
DECC (Harvey and Gray)[47]	Jan-10	UK	TRR
ARI (Kuuskraa)[48]	Dec-09	US, Canada, Poland, Sweden, Austria	"Recoverable resources"
Potential Gas Committee[49]	Jun-09	US	TRR
Theal[50]	May-09	US, Canada	OGIP and TRR
ICF (reported by [6])	Mar-09	US	TRR
IHS CERA [51]	Feb-09	Europe	TRR
Wood Mackenzie [52]	Jan-09	Europe	TRR

Notes:

[1]There have been a total of 16 Annual Energy Outlooks between 1997 and 2012. The AEO in 2003 used the same unconventional gas figures as 2002, while the 2011 estimate was based entirely on INTEK [3] and so is reported separately. There are therefore a total of 14 AEOs included in this row.

[2]USGS estimate based on Whidden *et al.* [14], Houseknecht *et al.* [53], Coleman *et al* [54]., Dubiel *et al.* [55], Higley *et al.* [56], Houseknecht *et al.* [57], Anna [58], Schenk *et al.* [59], Swezey *et al.* [60], Hettinger and Roberts [61], Finn and Johnson [62], Swezey *et al.* [63], Pollastro *et al.* [64] Higley *et al.* [65], Milici *et al.* [66] and USGS [67].

[3]Medlock indicates that resources should be commercially viable so his definition, although described as technically recoverable resources, could be closer to ERR.

[4]TRR can be derived through adding the EIA and INTEK figures for contemporaneous proved and inferred reserves, undiscovered resources, and 'unproved discovered technically recoverable resources', all of which are reported separately.

[5]ICF's 2011 report [29] indicates that there is a total of 61.5 Tcm of economically recoverable resource in the US and Canada. It provides a supply cost curve indicating that this volume is only recoverable at gas prices greater than $14/Mcf. Since this price is four times higher than current gas prices (around $3.5/Mcf on 15th December 2011), we consider that all of ICF's estimates are better interpreted as TRR.

Global

In this section we discuss several global estimates of unconventional gas resources which we then compare in Figure 5 below.

Estimates by Rogner [68] are key since many studies with estimates outside North America base their figure of his work. Rogner estimated the OGIP for each of the unconventional gases within eleven continental regions as shown in Table 3. Rogner's estimate of the global OGIP for unconventional gas was 920 Tcm, of which 50% was shale gas. Rogner did not provide a breakdown of OGIP in any individual countries, nor did he suggest or provide a fraction of these values that he considered recoverable, however numerous reports derive technically recoverable resources by taking certain percentages, or recovery factors, of Rogner's figures. Some values suggested or used include 15% by Mohr and Evans [39], 10-35% by MIT [6], and 40% by ARI [48] and the IEA [69].[1] To put these recovery factors in context, ARI [31] uses a range of 15% - 35% for the recovery of shale gas from each geological area analysed while recovery from conventional gas wells is often around 70-80% [70].

[1] The IEA does not explicitly state the recovery factor used for each of the three unconventional gases, but provides figures from which it can be calculated.

Table 3: Estimates of original shale gas in place by Rogner (1997)

Region	Original shale gas in place (Tcm)
North America	108.3
Latin America and the Caribbean	59.7
Western Europe[2]	14.4
Central and Eastern Europe[3]	1.1
Former Soviet Union	17.7
Middle East & North Africa	71.8
Sub-Saharan Africa	7.7
Centrally Planned Asia & China	99.4
South Asia	65.2
Other Pacific Asia	8.8
Pacific OECD	0
Total	**454.1**

Using Rogner's OGIP estimates, a 15% recovery factor would give a global estimate of 68 Tcm for the TRR of shale gas, while a 40% recovery factor would increase this to 181.3 Tcm. Hence, the range of 15-40% in the recoverable fraction of Rogner's OGIP corresponds to an uncertainty of around 113.3 Tcm on a global scale. This approximates to one third of the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)'s estimate of remaining global technically recoverable resource of conventional gas (~425 Tcm) [71].[4]

In Figure 5 we present the 15-40% recovery factors to demonstrate the range of estimates based on Rogner's work rather than all of the individual estimates.

[2] Western Europe is described as consisting of: Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Lichtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

[3] Central and Eastern Europe is described as consisting of: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, FYR Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, and Yugoslavia.

[4] 187 Tcm, or 44% of the total remaining technically recoverable resources of conventional gas, is classified as proved reserves in the 2011 BP statistical review [72]. Note however that this 'proved' figure covers all four types of gas (conventional, tight CBM and shale) to differing degrees in different countries, depending upon the state of development of the resource.

A more recent report by the World Energy Council ('WEC') in 2010 also provided OGIP figures for regions similar to those used by Rogner [38], although South Asia, Other Pacific Asia and OECD Pacific were combined into one region. Some of the estimates provided are significantly different to Rogner's, with the estimated OGIP for Latin America and Centrally Planned Asia & China decreasing to 10.6 Tcm and 10.5 Tcm (a reduction of around 80% and 90% respectively from Rogner's figures) while the OGIP estimated for the Former Soviet Union is 153 Tcm (an increase greater than eightfold). Regarding recovery factors, it is mentioned that *'nearly 40% of this endowment would be economically recoverable'*, corresponding to a global ERR of around 170 Tcm. Given that the costs of extraction and market conditions at the time when the resource will be extracted is highly uncertain, particularly in areas where there is currently no shale gas production, it is likely that the WEC's estimate actually corresponds more closely to TRR rather than ERR.

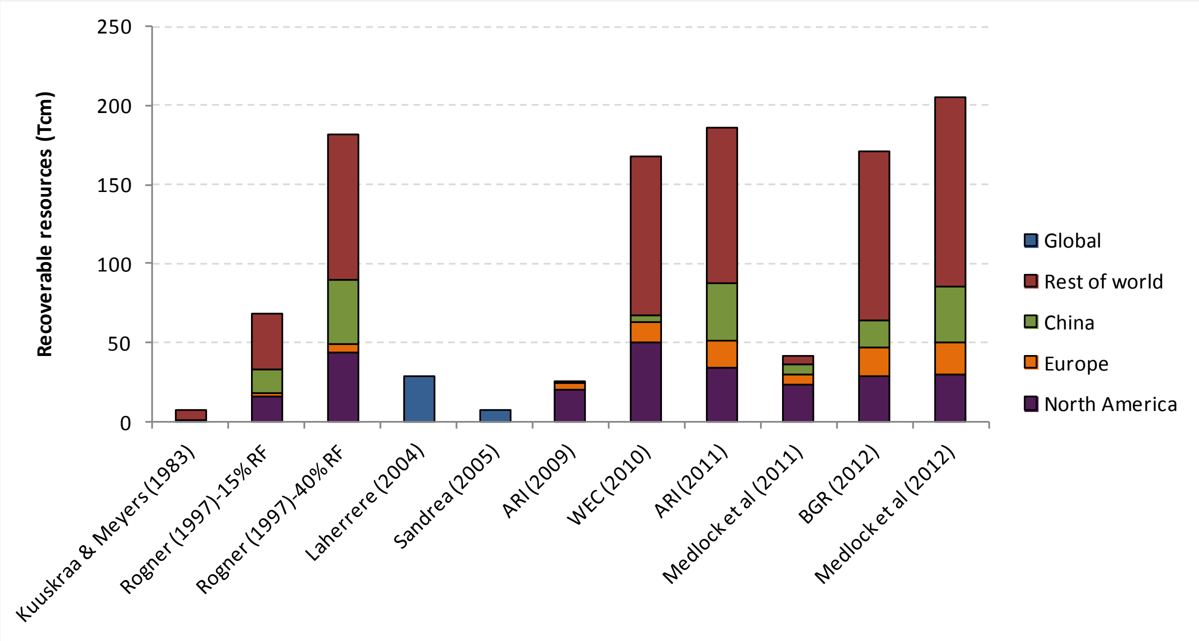
Two other recent independent reports have been undertaken which estimate technically recoverable shale gas resources on a global scale [28, 31]. Nevertheless, even these do not attempt to assess all shale plays and indicate that there is limited geological information available for a number of plays anticipated to hold shale gas.

ARI [31] for example ignores regions where there are large quantities of conventional gas reserves (Russia and the Middle East) or where there is insufficient information to carry out an assessment. Similarly, Medlock *et al.* [28] only assess the shale gas potential in six countries[5] outside North America and justify the exclusion of unassessed shales by suggesting that they are unlikely to be economically recoverable. Hence, neither review provides a global estimate of technically recoverable shale gas resources. The estimates of BGR [23] and the most recent report by Medlock [19] were to a large extent based upon ARI's [31] estimates although modified estimates in some countries based on alternative data.

ARI [48] produced an earlier and much smaller estimate in 2009 but noted a number of other shale plays were likely to contain resources and had not been quantitatively assessed and that its estimate was therefore anticipated *to 'grow with time and new data'* [48]. The majority of the increase between ARI's estimate in 2009 and 2011 comes from this increase in the geographical coverage of the later survey (see Figure 5). Finally, three other estimates of global shale resources have been made [73-75]. These were produced some time before the recent increase in US production and although they will have been influenced by shale gas production history in the US, appear to be predominantly based upon expert judgment. This gives rise to 11 estimates which we present in Figure 5. These studies are inconsistent in terms of: a) the definition of resources; and b) the geographical coverage. However, they serve as the best available comparison of evidence on global shale gas resources. As noted above, the ARI study has become the new benchmark for the majority of global studies.

[5] The nine countries analysed are: the United States, Canada, Mexico, Austria, Germany, Poland, Sweden, China and Australia.

Figure 5: Estimates of global shale gas resources by sources considering regions outside North America



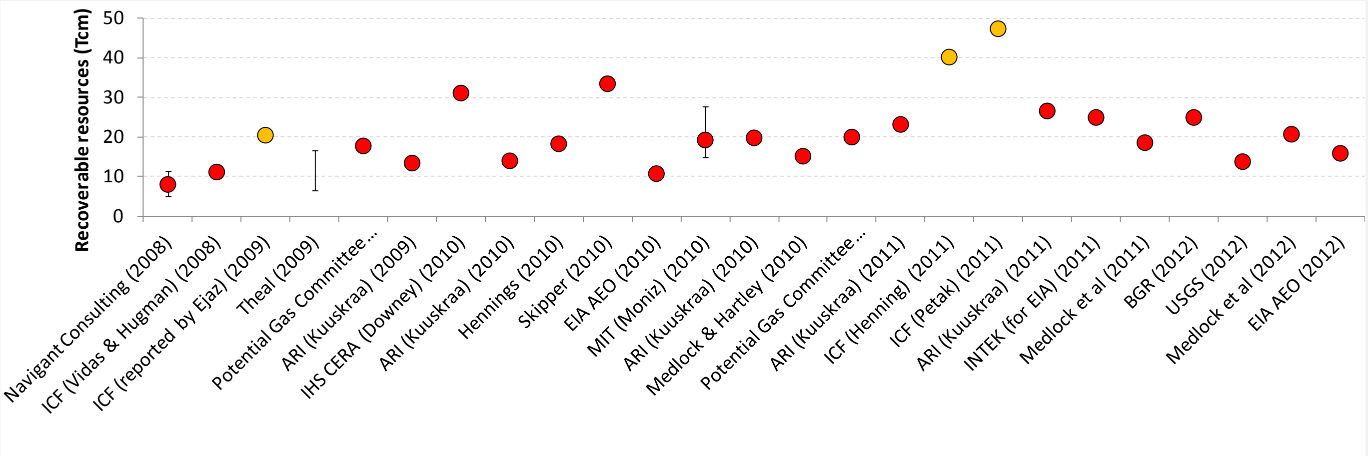
***Note*: Different studies cover different countries and regions and none provide a truly global estimate. Resource definitions also differ; both in terms of what is reported and how this is defined and estimated (see Table 2). Laherrere's estimate is URR, while Medlock's are likely to be closer to ERR. The OGIP estimate by Rogner is converted to TRR using 15% and 40% recovery factors and the WEC's estimate to ERR using a 40% recovery factor.**

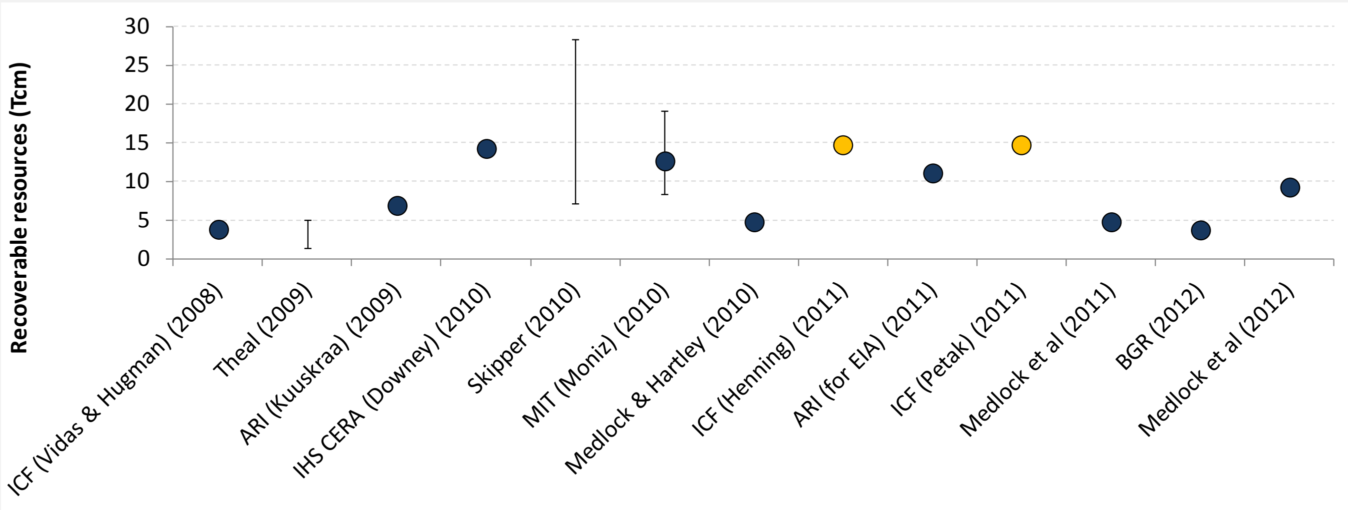
North America

Intuitively, the majority of available evidence provides some estimate of North American shale gas resources. Around 50% of the studies in our review provide estimates of shale gas resources in the United States. Also as we look at the development of these estimates over time they have increased. Figure 4 presents the increase in United States estimates over the past three decades, which appears to follow the United States increase in shale gas production over the same period.

Given the dramatic difference between historical and recent estimates we focus now on those estimates produced in the most recent years. In Figure 6 we present estimates of shale gas resource in the United States and Canada produced since 2008. There have been 25 for the United States and 13 for Canada. Some are updates of older reports [32, 33] but are reported here separately. Only three provide a range of uncertainty despite the apparent disagreement between studies and the uncertainty that implies. Even within the small time span the most recent estimates are on average higher than those made in 2008.

Figure 6: Estimates made since 2008 of the technically recoverable shale gas resources in the United States (top) and Canada (bottom). Points in yellow correspond to estimates that were stated as referring to economically recoverable resources.



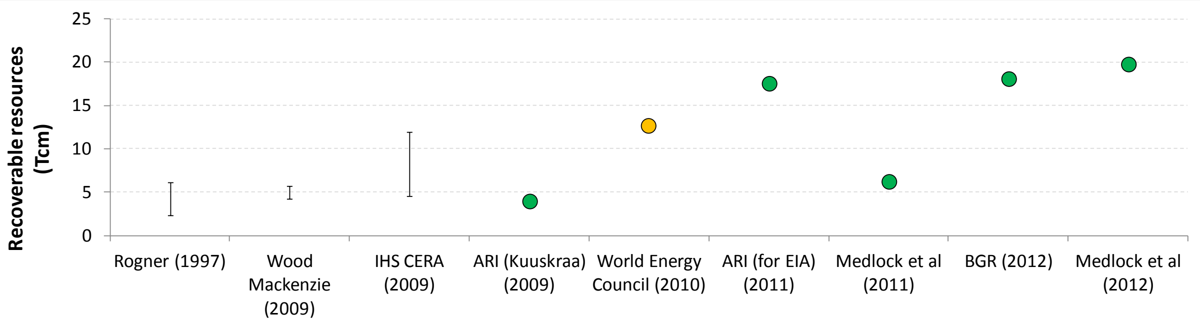


Note: **Some sources did not report a central estimate, only giving a range of values. The WEC [38] did not provide a split between the United States and Canada and so is not included.**

Europe

In contrast to the evidence base for the United States, few estimates of the recoverable resource of shale gas within Europe are available. A number of reports have been published since 2009, however, that focus specifically on the technically recoverable resources in Europe. These are presented in Figure 7, and range from 2.3 Tcm to 19.8 Tcm, with a mean of 10.6 Tcm. Note that ARI's estimate from 2009 ignored a number of plays.

Figure 7: All estimates of the technically recoverable resources of shale gas within Europe. The point in yellow corresponds to an estimate that was stated as referring to economically recoverable resources.



Note: **The range for Rogner's estimate is derived using a 15 – 40% recovery factor within Western and Eastern Europe. Values for Wood Mackenzie and IHS CERA come from Weijermars *et al.* [76].**

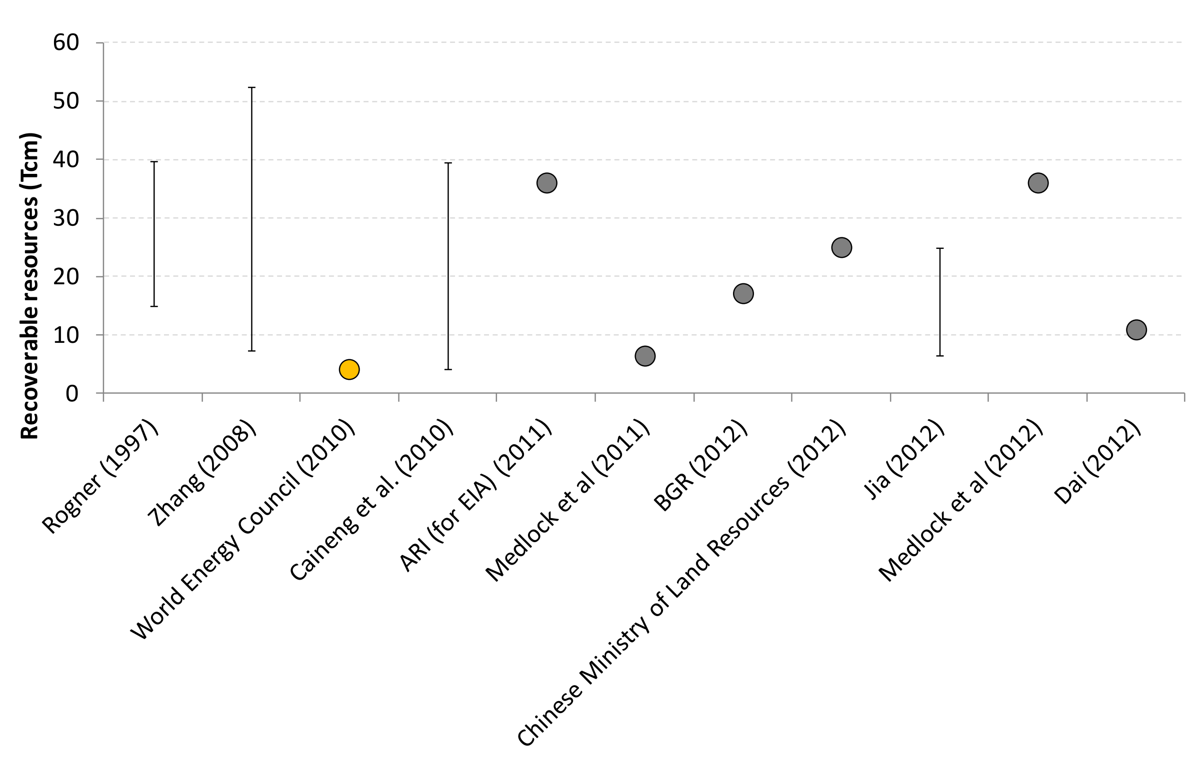
China

Until recently, relatively few estimates of the Chinese shale gas resource were available, most only providing estimates of the OGIP. From 1997 to 2011 there were six separate estimates for China. However, in the first six months of 2012 five new reports estimating shale gas resources were published. This is similar to the rapid development of US shale gas literature. These estimates are presented in Figure 8.

For those estimates which are of OGIP, we have again used a range of recovery factors between 15-40% since there is little agreement on this figure, applying this to the OGIP estimates of Rogner [68] and Caineng *et al.* [35].

The range seen in Caineng *et al.* results from applying this variation in recovery factor to the range of OGIP provided by the authors (28.3-99.1 Tcm). The WEC's estimate is for 'Centrally Planned Asia' (which includes Cambodia, Hong Kong, PDR Korea, Laos, Mongolia and Vietnam) as well as China but for illustrative purposes we assign all of the resource to China. This estimate was indicated by the authors to be ERR and is therefore designated by the yellow datapoint in Figure 8. Finally the Medlock estimate in 2011 is conservative based on perceived water constraints. However, Medlock published a more recent assessment [19] which matches the less conservative ARI estimate. The variation in currently available estimates for TRR in China is therefore even larger than that in Europe and North America, though more recent estimates have converged somewhat.

Figure 8: All estimates of the technically recoverable resources of shale gas within China. The point in yellow corresponds to an estimate that was stated as referring to economically recoverable resources.



Estimates of other unconventional gas

The 'other' unconventional gases are somewhat complicated given the inconsistency of the definition of unconventional gas found in the literature. Unconventional gas is frequently defined in terms of the permeability of the source rock. Rock permeability is measured in units called millidarcies (md) and in the past gas in rocks with a permeability of <0.1md had been classified as unconventional [77]. The rate of gas flow into a well is a function of permeability, but also of other variables such as reservoir pressure, well radius and gas viscosity. The use of one measure to define unconventional is therefore of limited usefulness.

An alternative approach defines unconventional gas in terms of the technologies needed to produce it at economically viable rates. In this vein the US National Petroleum Council (NPC) define unconventional gas as:

'natural gas that cannot be produced at economic flow rates nor in economic volumes unless the well is stimulated by a large hydraulic fracture treatment, a horizontal wellbore, or by using multilateral wellbores or some other technique to expose more of the reservoir to the wellbore.' [77]

However, neither approach provides a concrete definition. In the example of oil, unconventional oil is defined by its characteristics. Kerogen from oil shale, or bitumen from oil sands is characteristically different from the light, sweet crudes considered conventional, and this distinction is therefore fixed. However, other types of conventional oil have previously been considered unconventional based on technological or economic grounds. Deepwater oil, once considered unconventional given the technological challenges and economic cost of its extraction, is now commonly considered within conventional oil estimates. The only physical characteristics that can be used to categorise natural gas are the contaminants or impurities it contains, yet wet or sour gas for example are rarely if ever considered unconventional gases. . The separation of conventional and unconventional gas therefore relies on temporally variable measurements of technology and economics. Given the similarities it seems intuitive that definitions will change over time as they have done for oil and this is already materialising in some studies which now classify tight gas as a conventional resource [23]. It is also possible that other gases may be included under this techno-economic classification of unconventional gas, including Arctic gas or stranded gas (gas in very small fields). Below we consider CBM and tight gas as the 'other' unconventional gases, acknowledging that this classification may not hold in the future[6].

There are few estimates of either CBM or tight gas. For both types of gas the best data is for the United States.

The main uncertainty affecting tight gas is the absence of any studies providing global disaggregated tight gas estimates, discounting Rogner's OGIP estimates [68]. Rogner indicated that his tight gas estimates, which are still used by many sources [78-80], relied upon the upper end of a global estimate of OGIP from Kuuskraa and Meyers [73], and should be considered 'conservative'. This was allocated geographically using the regional distribution of conventional gas. It is not clear from where Rogner's upper figure of 215 Tcm OGIP has arisen however.

Kuuskraa and Meyers [73] indicate only 85 Tcm for tight gas in place globally, 60% less than Rogner. 57 Tcm of this estimate, the volume estimated for all regions outside the United States and Canada, was itself based upon a report by Meyer [81] first published in 1979. Meyer's estimate was purely speculative however and seemingly based upon expert judgement rather than a repeatable method or metric [81]. Therefore we cannot verify the source of Rogner's global estimate, and the only other global estimate is now over 30 years old and was entirely speculative.

An estimate of tight gas OGIP and TRR was given by Total in a promotional brochure [82] which suggested that between 20-50 Tcm was recoverable globally from an in place resource of 310-510 Tcm, and similarly BGR [83] indicated a recoverable figure of 46 Tcm globally. In both cases however no indication is given as to how these figures have been derived or from where they are taken.

Tight gas is nevertheless reported at some regional and country levels. Recent estimates of US tight gas resources range from 6.0 - 17.3 Tcm [33, 40] with the USGS [67] toward the lower end of this range with an estimate of 8.2 Tcm and the EIA most recently estimating 14.5 Tcm [15]. Recoverable Canadian tight gas is estimated to be of a similar size with a range of 6.5 - 14.5 Tcm [41] while recoverable Chinese tight gas is estimated at 8.8-12.1 Tcm [21]. These more disaggregated figures, which sum to around 32.5 Tcm if the mid-points of ranges are taken and which are only for three countries, suggest that a global estimate around 50 Tcm may be conservative.

The report by Total [82] highlights another crucial uncertainty with tight gas resources, namely an appropriate recovery factor. Total's figures indicate a recovery factor between 6-10%. A very different figure of 40% is applied to Rogner's estimates by the IEA [79] but it does not indicate how this figure was estimated nor why it is double the recovery factors used for many of its shale gas TRR estimates. An even greater figure is given by ICF [84] which again adopts Rogner's figures but assumes a 40% recovery factor in a `low case' scenario and 65% in a `high case' scenario, similarly Jia *et al.* [21] use a recovery figure of around 50% for Chinese tight gas resources.

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[6] Other resources such as methane hydrates could also be considered unconventional gas, though those are not covered here.

The paucity of global estimates of tight gas may be a function of the fact that this gas type is sometimes classified as conventional, and therefore not included in reports examining unconventional resources. However, new studies examining tight gas at a global level are certainly required and would vastly improve the quality of information regarding this resource.

As shown in Figure 3 estimates of tight gas resources for the US have grown by over 4 Tcm in the past 15 years, and are now similar in magnitude to shale gas estimates, though receive considerably less attention in the literature.

Only two estimates to have provided global, disaggregated estimates of CBM resources [23, 48] and so again the major uncertainty in estimates of CBM resources is the lack of publically available information.

An interesting point to note for CBM resource estimates is that they have showed relative consistency over time. Figure 3 indicates that while shale and tight gas resource have increased significantly over the 15 year period for which estimates are available, CBM resources have increased by a modest 2 Tcm and remained less than 4 Tcm over the same period. A similar pattern is seen in estimates of global CBM resources.

Kuuskraa previously published an estimate of CBM resources in 1998 [85], and while the 2009 assessment [48] is around 60% greater than this, its shale gas estimates have increased by a far greater proportion over a similar period: its estimates for the United States for example have increased by around a factor of eighteen between 1996 and 2011. In addition, the two estimates by Kuuskraa and BGR are relatively consistent for a large proportion of countries for which both have produced estimates although it is unclear the extent to which these have relied upon each other. Other country level estimates are also available for the US, China, Canada and Australia and we take these into account in developing the range of CBM resource estimates.

Although one cannot rule out major technological breakthroughs that could dramatically increase CBM resources, and while there are a limited number of reports examining CBM resources, it appears on the basis of the consistency and proximity of current estimates, the uncertainty in CBM resources appears to be quantitatively lower than for the other unconventional gases.

4. Estimates in context

Table 4 summarises the mean estimates for unconventional gas RTRR for a number of regions globally as well as estimates for the RTRR of conventional gas to provide some context. This table is not intended to provide new estimates for unconventional gas resources, but presents an overview of the current estimates that exist for natural gas and in particular display the ranges that exist in estimates for technically recoverable shale gas resources.

The conventional estimates are based upon the ‘remaining potential’ data from the 2011 BGR [83] report, which gives estimates for conventional gas only. As mentioned above, the 2012 edition of this report [23] includes tight gas resources in the 'conventional' category and so cannot be used.

For the tight gas figures we have where possible avoided using the figures of Rogner, given the problems with these mentioned above. For the US, we have taken the average of the estimates of [15, 33, 40, 67]; for Canada we take the mid-point of estimates from [41]; for China we average the mid-point of the estimates from [21] and [18]; for Australia, Total [82] present a figure for a ‘China and Australia’ region and so we subtract the previous China figure from this value; finally we also take Total’s figure for the CIS. Given the absence of available data in other regions, there are no existing alternative options to using Rogner’s figures. There is also the uncertainty discussed above relating to the wide range of estimates for the recovery factor for tight gas. Therefore while estimates are based on an old source of unclear origin and estimates of recovery factors that are very poorly constrained, they do at least allow a better comparison between the gases if at least all regions are covered to some extent. Where we have adopted Rogner's figures we have assumed a value of 10% recovery factor, the upper end of the range given by Total [82].

For the CBM resources, all countries take either the BGR [23] or Kuuskraa [48] figures or an average if both are given except for: Australia for which we also include the estimate from [86]; for Canada for which we also include the estimate from [40, 41]; for China we take the average of [21] and [18]; and finally for the US we include in the average the estimates from [15, 34, 40, 67].

Table 4 also presents our review of current best estimates for the shale gas resources. Sources and the reasons for their choice for each region are summarised in the final column of Table 4.

Table 4: Estimates of the remaining technically recoverable resources of conventional, CBM, tight and the ranges resulting from choosing the most appropriate current estimates for shale gas (Tcm)

Region	Conventional	Tight	CBM	Shale – Best estimates Low	Shale – Best estimates Central	Shale – Best estimates High	Basis of shale gas estimates
Africa	30.9	2.3	0.9		29.3		Algeria, Libya, Tunisia, and South Africa: [31] Morocco: mean of [31] and [19]
Australia	5.1	4.3	4.5		11.2		[31]
Canada	8.8	10.5	2.3	3.6	12.0	28.3	High: [42] Central: mean of [19, 29, 31, 40, 42, 46] Low: [41]
China	12.5	10.7	11.2	6.5	17.8	36.1	High: [31] Central: mean of [18, 22, 23] Low: Lowest value from [21]
CIS	181.2	5.4	11.4		11.6		Kaliningrad and Ukraine: [31] Lithuania: mean of [31] and [19] Russia: [23]
CSA	17.1	3.7	0.2		35.6		Bolivia, Brazil, Chile, Paraguay, Uruguay, and Venezuela: [31] Colombia and Argentina: mean of [31] and [19]
Europe	14.3	1.2	1.5		15.9		Poland: mean of [31] and average of max and min areas with central EUR/well from [16] (557 Bcm) Austria: [19] UK: mean of [31], [19] , [47] Germany: mean of [31], [19], central estimate from [20] Denmark, France, Netherlands, Norway, Sweden, and Turkey: [31]
India	2.0		0.9	0.2	1.8	2.4	High: [19] Central: [31] Low: [25]
Japan	0.0	0.0	0.0		0.0		No sources report any shale gas to be present in Japan
Middle East	110.7	2.3	0.0	2.8		28.7	High: whole of Rogner's [68] MENA region with 40% recovery factor Low: half of [38] MENA region (as assumed by [31]) with 15% recovery factor
Mexico	1.9		0.2	4.2	11.4	19.3	High: [31] Central: mean of [31], [19] and central of range of estimates from [24] (8.6 Tcm) Low: low estimate from [24]
ODA	21.0	2.0	2.2	1.3		22.1	High: Rogner [68] 'Other Pacific Asia' and 'Centrally Planned Asia' regions with 40% recovery factor minus best estimate of China from above Low: 'Other Pacific Asia' only (as assume all of Rogner's 'Central Planned Asia' is China) and assuming a 15% recovery factor. This is similar to estimate for Pakistan only from [31]
South Korea	0.1	0.0			0.0		No sources report any shale gas to be present in South Korea
United States	27.1	11.8	4.0	13.8	19.3	47.4	High: highest estimate available - [29] (assumed to be TRR) Central: mean of most suitable estimates - [17, 19, 30] and [67] (with shale plays added that are not included in this summary) Low: lowest estimate available since January 2010 : USGS [67]
Global	**432.5**	**54.2**	**39.2**		**193.2**		(Taking the mid-point of estimates for those regions for which there is no central estimate)

Notes: CSA = Central and South America, CIS = Commonwealth of Independent States, ODA = Other Developing Asia

Focusing on the central estimates within Table 4 the figures suggest that the United States holds around 10% of the global TRR of shale gas, while Europe holds around 7%.

It is also of interest to place global shale gas resources into context with the global remaining recoverable resources of conventional gas. The mean estimate given in the table above of the global TRR for shale gas is around 45% of the remaining recoverable resources of conventional gas.

The remaining global TRR of all natural gas consists of the sum of the mean estimates of conventional gas and the three unconventional gases. On a global scale, shale gas is estimated to make up 27% of the total figure of 719.1 Tcm. On a regional basis, however, shale gas can form a much larger proportion of the remaining TRR. For example, using the mean estimates, shale gas is estimated to represent 36% of the remaining TRR of natural gas in China, 48% in Europe and 63% in Central and South America. This suggests that the impact of shale gas is likely to be greater at the regional level than at the global level.

5. Conclusions

This paper focuses on original estimates of global unconventional gas resources and reviews the available literature providing such estimates. That analysis reveals the importance of explicitly and consistently defining resource estimates to ensure meaningful and comparable data.

There is an absence of rigorous studies for a number of key regions across the world. For shale gas this includes Russia (CIS) and the Middle East, which are estimated to hold potentially very large resource volumes (Table 4). While Rogner [68] and the World Energy Council [38] provide independent estimates for these regions, they provide very little information on their methodology and their methods are potentially inaccurate. Rogner’s work is particularly concerning given its pivotal role in a number of studies. The use of US analogues, for example, has the potential to significantly bias results, and the use of an alternative analogue may provide significantly different estimates.

Tight gas and CBM are less well studied, and estimates of their global resource are scarce. For both types of gas the best evidence is available for the United States. Tight gas is occasionally classified as conventional, and this may be reflected in the fact that there are no global disaggregated studies reporting tight gas TRR. Rogner’s OGIP estimates are therefore the only globally disaggregated assessment of tight gas, and we have used a 10% recovery factor to generate an estimate of TRR. There are two globally disaggregated studies of CBM and estimates seem to have been relatively consistent over time, suggesting that CBM estimates are relatively less uncertain, though significantly smaller than shale gas estimates.

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