Energy Policy 87 (2015) 654–664

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Uncertainty in the availability of natural resources: Fossil fuels, critical metals and biomass

Jamie Speirs[a], Christophe McGlade[b], Raphael Slade[a,*]

[a] Imperial College Centre for Energy Policy and Technology (ICEPT), Imperial College London, South Kensington Campus, London SW7 1NA, UK
[b] University College London (UCL) Energy Institute, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK

HIGHLIGHTS

- Resource estimates are highly uncertain, frequently incommensurable, and regularly contested.
- Data limitations need to be overcome, and methodologies harmonised and improved.
- Sustainability and socio-political uncertainties are frequently neglected.
- Uncertainties are dynamic, but reducing uncertainties inevitably involves trade-offs.

ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form
12 February 2015
Accepted 25 February 2015
Available online 29 March 2015

Keywords:
Energy resources and reserves
Resource potential
Critical metals
Fossil fuel
Biomass
Uncertainty

ABSTRACT

Energy policies are strongly influenced by resource availability and recoverability estimates. Yet these estimates are often highly uncertain, frequently incommensurable, and regularly contested. This paper explores how the uncertainties surrounding estimates of the availability of fossil fuels, biomass and critical metals are conceptualised and communicated. The contention is that a better understanding of the uncertainties surrounding resource estimates for both conventional and renewable energy resources can contribute to more effective policy decision making in the long term. Two complementary approaches for framing uncertainty are considered in detail: a descriptive typology of uncertainties and a framework that conceptualises uncertainty as alternative states of incomplete knowledge. Both have the potential to be useful analytical and communication tools. For the three resource types considered here we find that data limitations, inconsistent definitions and the use of incommensurable methodologies present a pervasive problem that impedes comparison. Many aspects of resource uncertainty are also not commonly captured in the conventional resource classification schemes. This highlights the need for considerable care when developing and comparing aggregate resource estimates and when using these to inform strategic energy policy decisions.

1. Introduction

The global energy system consumes vast quantities of natural resources. Some of these resources are finite (e.g. fossil fuels), some are renewable (e.g. biomass), and some, for example the metals required for permanent magnets in wind turbines, are finite but may be recycled. Scenarios for how the global energy system might evolve play an important role in informing the policy debate and are strongly influenced by resource availability and recoverability estimates (DTI, 2007). Yet these estimates are often highly uncertain, frequently incommensurable, and regularly contested. For example, fears over the availability of oil, have frequently led to statements that a transition to alternative energy sources will be necessary to avoid the socially disruptive effects of increasing prices (Helm, 2011, Maugeri, 2009).

Bioenergy is a renewable energy option that has arguably the greatest potential to substitute for oil, but here also there is uncertainty over its future availability. In particular, the interlinkages between biomass and food production have generated a high profile and divisive debate about whether large-scale adoption of bioenergy can be truly sustainable and the extent to which policy support can be justified (Slade et al., 2011b). In the case of other renewable energy infrastructure such as wind turbines and solar cells, these will only be able to make a significant contribution to global energy provision if large quantities of the critical metals[1]

---

* Corresponding author.
E-mail address: raphael.slade@imperial.ac.uk (R. Slade).

[1] The list of metals considered as *critical metals* is not fixed, but typically includes: Cobalt, Platinum Group Metals, Gallium, Rare Earth Elements (REEs), Germanium, Selenium, Indium, Silver, Lithium, and Tellurium (Speirs et al., 2013a).

http://dx.doi.org/10.1016/j.enpol.2015.02.031

required for their production are available. The emergence of resource nationalism in response to real, or perceived, supply constraints could restrict access to these metals and this may ultimately limit the rate at which such technologies are adopted (Moss et al., 2011; Hayes-Labruto et al., 2013). Sources of uncertainty such as these provide the context in which strategic energy policy and resource management decisions must be made.

This paper explores how the uncertainties surrounding estimates of the availability of fossil fuels, biomass and critical metals are conceptualised and communicated. The nature of the uncertainties in these resource estimates has been examined by a number of analysts (see e.g. Sorrell, et al. (2010), Slade et al. (2011a), Mcglade et al. (2013a, 2013b)), yet the importance of understanding and quantifying uncertainty in resource estimates is often downplayed. Analysts also frequently fail to quantify or even acknowledge the uncertainty in the estimates they produce (IIASA, 2012, ARI, 2013). The result is a very wide range of estimates of 'available' resources that has the potential to cloud debate, confuse policy makers, impede effective action and foster further uncertainty and ambivalence (Lynd et al., 2011, Pearson et al., 2012). This is particularly the case for resources such as biomass and unconventional gas where the regulatory and policy incentive framework is less established.

The contention of this paper is that a better understanding of the uncertainties surrounding resource estimates for both conventional and renewable energy resources can contribute to more effective policy decision making in the long term. Our argument is presented as follows. Section 2 describes alternative approaches to conceptualising and categorising uncertainty in resource estimates. Section 3 introduces the dominant resource classification schemes currently used for energy resources. Sections 4, 5 and 6 discuss sources of uncertainty in fossil fuel, critical metal and biomass resource estimates respectively. Conclusions and policy implications are presented in Section 7.

2. Understanding uncertainty

Uncertainty in resource estimates stems from a variety of issues about which knowledge may be incomplete. Uncertainty, however, is a subtle concept used to mean different things in different contexts and disciplines (Thunnissen, 2003). In framing uncertainty for the discussion in this paper, two complementary approaches are presented. The first presents a typology of uncertainties and provides examples of how they might apply to fossil, metal and biomass resources. The second conceptualises uncertainty as alternative states of incomplete knowledge.

2.1. A typology of uncertainty

Uncertainties can be categorised according to their origin and impact. A typology frequently applied to fossil, metal and biomass resources estimates classifies gaps in knowledge as arising from either: physical, technical, economic, socio-political or sustainability uncertainties.

Physical uncertainties arise from imperfect data and imprecise measurement. The extent of an oil reservoir (or whether an oil reservoir exists), for example, may be based on a limited number of exploratory wells and seismic data. These techniques can only provide an imperfect estimate of the reservoir's area, volume and quality. In general, physical uncertainties may be reduced with improved sampling and repeated measurement, but this will normally entail additional cost.

Technical uncertainties relate to imperfect knowledge about the effectiveness of technologies used to extract resources. For example, the primary recovery phase of oil production only relies on the existing pressure of the reservoir. Once that pressure decreases and production slows, secondary and tertiary production techniques may be applied to artificially increase the well pressure, or influence the physical properties of the oil within the reservoir. This can significantly increase production rates in the short term and will influence the total volume of oil recovered. Estimating the potential impact of these interventions and the resulting recovery factor is difficult and varies across projects.

Economic uncertainties relate to assumptions about the future economic viability of resource extraction, including market prices, extraction costs and the availability of alternatives. If costs are high, and prices low, the quantity of recoverable commodity may be small as only the easiest and cheapest proportion of the commodity will be recoverable at a profit.

Socio-political uncertainties relate to the potential impact of current or future policy decisions or social interventions. Policy makers may change licensing rules, tax regimes, or the ownership structures of asset leases, changing the viability of affected projects. Similarly, public opposition or support for particular projects may influence the recoverability of a resource through legal, political or other channels.

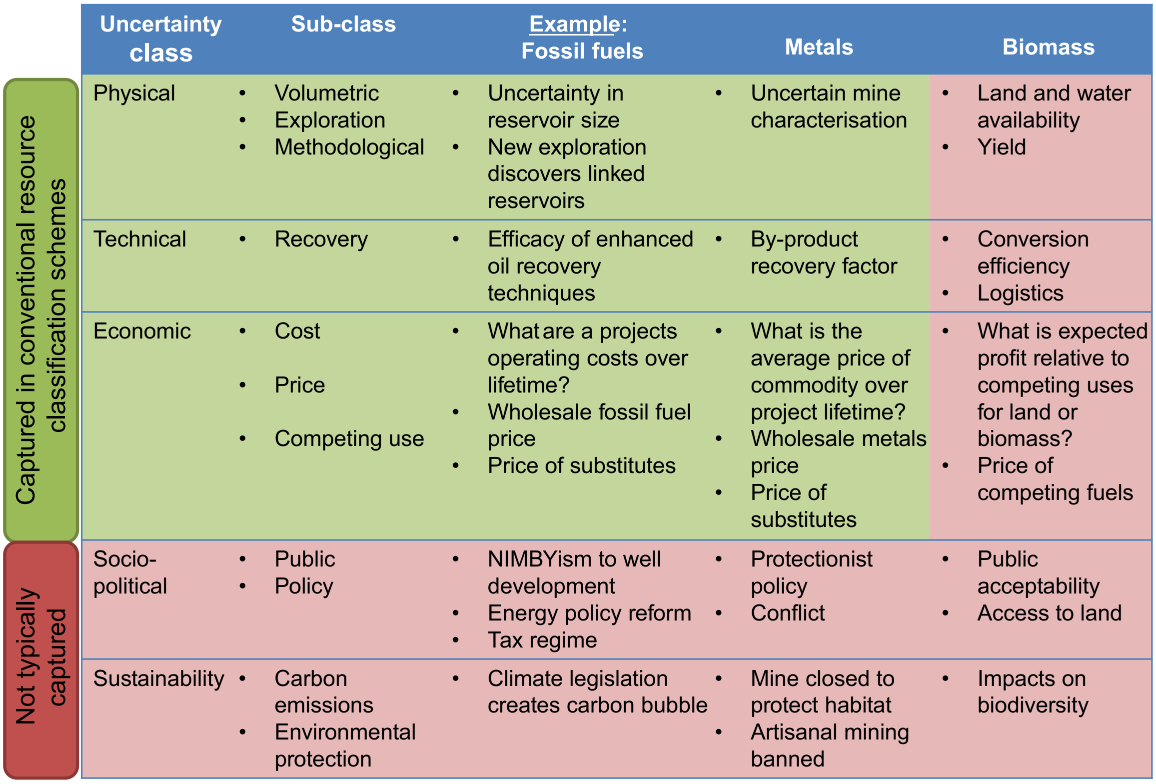
Sustainability uncertainties relate predominately to the environmental and social implications of resource recovery. This might include the concerns over biomass production and its interactions with food production (the 'food vs. fuel' debate (Eide, 2008)), or the greenhouse gas implications of extracting and burning fossil fuel reserves (the so-called 'carbon bubble' debate (Leaton, 2011)). Sustainability uncertainties can influence the overall viability of individual projects either through policy or through the imposition of physical limits. For example, climate policy might dictate that fossil fuels should be left in the ground placing known fossil fuel reserves off limits. This type of uncertainty is intrinsically linked to the 'socio-political' and 'physical' dimensions, but is worth considering separately given its growing importance.

This typology is summarised in Fig. 1. Physical, economic and technical uncertainties are generally captured within the traditional resource classification schemes, although issues arise with consistency and transparency (discussed further in Section 3). In contrast, socio-political and sustainability uncertainties are typically not incorporated even though they may have significant impacts on the availability of resources.

2.2. Dimensions of incomplete knowledge

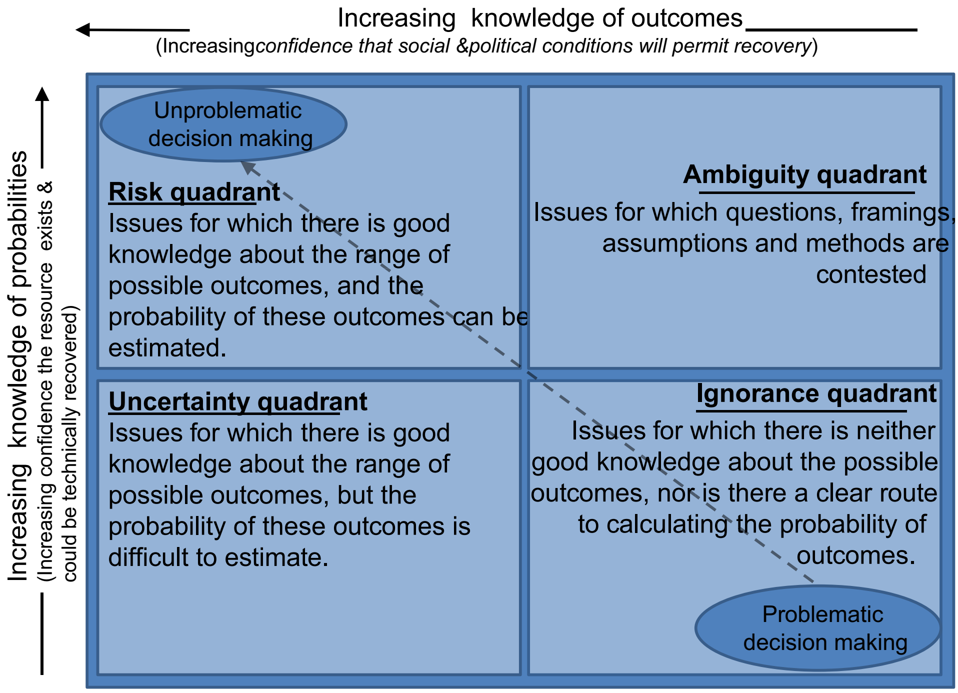
An alternative way of conceptualising uncertainty described by Stirling (2010) considers two dimensions of incomplete knowledge: the *extent of knowledge about a potential hazard or outcome*, and the *likelihood or probability of that outcome*. In the case where there are no significant gaps in knowledge an estimate of the impact of a known outcome can be combined with a discrete estimate of probability to provide an estimate of *risk*. In many cases, however, it may not be possible to know what the potential outcome will be, or its probability of occurrence. If knowledge about both these dimensions is complete or incomplete, then combining them gives rise to four contrasting states of incomplete knowledge, shown in Fig. 2, and characterised as: *Risk, Uncertainty, Ambiguity*, and *Ignorance* (Stirling, 2007, 2010).

There are a number of ways in which the axes in Fig. 2 could be interpreted with regard to estimating resource availability. However, the most straightforward is to interpret them in terms of *confidence about whether a resource exists and can be technically recovered* (*y*-axis: knowledge of probabilities) and *confidence about the social and political condition that will permit recovery* (*x*-axis: knowledge of outcomes). In this way, the *y*-axis takes into account many of the physical, technical and economic aspects of resource



	Uncertainty class	Sub-class	Example: Fossil fuels	Metals	Biomass
Captured in conventional resource classification schemes	Physical	• Volumetric • Exploration • Methodological	• Uncertainty in reservoir size • New exploration discovers linked reservoirs	• Uncertain mine characterisation	• Land and water availability • Yield
	Technical	• Recovery	• Efficacy of enhanced oil recovery techniques	• By-product recovery factor	• Conversion efficiency • Logistics
	Economic	• Cost • Price • Competing use	• What are a projects operating costs over lifetime? • Wholesale fossil fuel price • Price of substitutes	• What is the average price of commodity over project lifetime? • Wholesale metals price • Price of substitutes	• What is expected profit relative to competing uses for land or biomass? • Price of competing fuels
Not typically captured	Socio-political	• Public • Policy	• NIMBYism to well development • Energy policy reform • Tax regime	• Protectionist policy • Conflict	• Public acceptability • Access to land
	Sustainability	• Carbon emissions • Environmental protection	• Climate legislation creates carbon bubble	• Mine closed to protect habitat • Artisanal mining banned	• Impacts on biodiversity

Fig. 1. A typology of uncertainties affecting the estimation of future resource availability for fossil fuel, critical metal, and biomass resources.



Issues for which there is good knowledge about the range of possible outcomes, and the probability of these outcomes can be estimated.

Issues for which questions, framings, assumptions and methods are contested

Issues for which there is good knowledge about the range of possible outcomes, but the probability of these outcomes is difficult to estimate.

Issues for which there is neither good knowledge about the possible outcomes, nor is there a clear route to calculating the probability of outcomes.

Fig. 2. Contrasting states of incomplete knowledge.
Source: Adapted from Stirling (2010).

estimation that are systematically addressed in conventional reserve and resource classification schemes (discussed in detail in Part 3). The *x*-axis, in contrast, indicates how well the consequences associated with developing a resource are understood and takes into account socio-political aspects, normative sustainability constraints, and the extent to which there may be fundamental disagreement about the framing of possible outcomes. Thus in the bottom left *uncertainty quadrant* the gaps in knowledge are primarily physical and technical. Whereas in the top right *ambiguity quadrant* the gaps in knowledge relate to outcomes, the existence and extent of which society might be reluctant to test. An example of a resource that might reasonably be argued to fall within the ambiguity quadrant is Canadian tar sands: the extent and practicality of recovering this resource is comparatively well understood, but the social legitimacy of attempting to do so remains highly contested. For all resources, accumulating additional experience has the potential to change our knowledge of the situation and in this way we may move around the matrix.

3. Classifying and categorising resources and reserves

Resource estimates are important because they provide companies (and countries) with a systematic way to quantify and value their assets and communicate this to investors. At a strategic level, resource estimates also underpin modelling of future energy trends and guide policy making by governments, and international organisations. The best developed classification frameworks are those applied to fossil fuels. We describe these in detail here as many of the concepts and much of the terminology is equally applicable to critical metals and biomass.

Energy companies and analysts have historically applied a range of methods to quantify their resources and reserves. As a result estimates produced by different companies are often not directly comparable. There are also geographical differences, with regions such as the Former Soviet Union, and the United States applying significantly different classification systems (Henley and Allington, 2012). This is often of little consequence to an individual company, but is of much more significance to those comparing or aggregating reserve and resource estimates at a national or supranational level. In an effort to improve the comparability of resource estimates, several organisations have sought to standardise the way reserves and resources are reported. Equity market regulators – US Securities Exchange Commission (SEC) and UK Listing Authority (UKLA) – prescribe rules that detail how companies listed on their exchanges should report reserve estimates (SEC, 2008, Ukla, 2012). These rules, however, only partially address issues of comparability and transparency. More recently international organisations have proposed classification schemes that aim to unify reporting. These include the Society of Petroleum Engineers (SPE) Petroleum Resources Management System (PRMS), and the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) (SPE et al., 2008, UNFC, 2009). The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) is a third standard, developed specifically for solid mineral reserves reporting. The UNFC can be applied directly, or used as a 'harmonising tool' to aid in the fair comparison of different classification systems, including PRMS and CRIRSCO. While each of these classification systems has unique elements, the broad categories they describe can be represented as a simple hierarchy, shown in Fig. 3.

For any fossil fuel or metal resource there is an initial quantity that exists within the field or mine. Geologists can estimate this quantity based on a range of geological and sensing data gathered during exploration. In the case of fossil fuels this is referred to by various names – Original Oil In Place (OOIP), Original Gas In Place (OGIP), Stock Tank Oil Initially In Place (STOIIP), etc. – and is referred to in Fig. 3 as the 'Total commodity initially in place'. Given physical conditions and economic constraints only a fraction of this will likely be recovered, and a specific quantity may have already been produced. Of the remainder, a proportion may be producible at current extraction costs and commodity prices using existing technologies. This is referred to as *economically recoverable* in Fig. 3, although the term *commercial projects* may also be used. The term *reserves* is sometimes used interchangeably with the term *economically recoverable*, but in most classification schemes additional criteria, such as a reasonable timeframe[2] for the project to be developed, must also be satisfied. Therefore reserves in Fig. 3 are shown as a fraction of the economically recoverable resource.

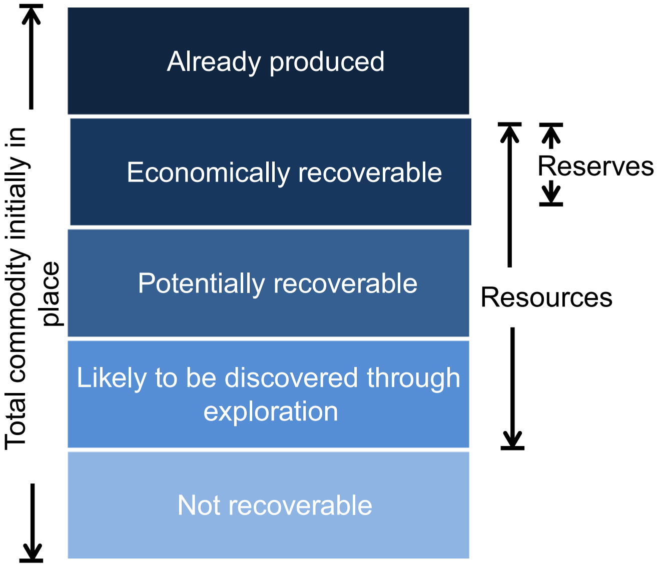


Fig. 3. Generic representation of a resource classification hierarchy.

Reserves may be further subdivided according to the probability that they can be recovered. For example, the SPE-PRMS divides this category into three sub-categories which are estimated deterministically: proved (1*P*), proved and probable (2*P*), and proved, probable and possible (3*P*). In this scheme 1*P* represents a conservative assessment of reserves, 2*P* represents a central estimate of reserves, and 3*P* represents an optimistic estimate of reserves. The SPE-PRMS also allows for a probabilistic approach to reserve estimation which includes three sub-categories – *P90, P50 and P10* – analogous to the deterministic sub-categories mentioned above but with a 90%, 50% or 10% probability of being exceeded by the time production ceases. It is also preferable to provide a probability distribution over reserves rather than single point estimates, but in practice this is rare.

A proportion of the *commodity initially in place* identified by geological and sensing data may be deemed producible given existing technology, but uneconomic at current commodity prices. This quantity is often referred to as *contingent resources*. The UNFC further subdivides this category into *potentially commercial* and *non-commercial* projects. In Fig. 3 this category is referred to as *potentially recoverable*. As technology advances and/or economics improve, *potentially recoverable* resources may be re-categorised as *economically recoverable reserves*, and *unrecoverable resources* may be reclassified as *potentially recoverable*. The former process is often called *reserve growth*,[3] although reserve growth also encompasses the discovery of additional connected reservoirs, changes in definitions etc. The potential for new quantities of fuels and metals to be discovered is often referred to as *exploration projects* or *prospective resources* (shown as *likely to be discovered through exploration* in Fig. 3).

The sum of *economically recoverable*, *potentially recoverable* and *likely to be discovered through exploration* categories is often referred to simply as *resources*. If one assumes that only existing

---

[2] There is no precise definition of how long a period is 'reasonable'. The SPE-PRMS indicates that this will depend on project-specific circumstances, although it gives five years as a benchmark.

[3] The term reserve growth can cause confusion as reserves in a region are constantly being depleted due to production and increasing with discoveries of new fields. Reserve growth is thus growth of an initial reserve estimate or of the total volume of oil recoverable excluding any contribution from new field discoveries.

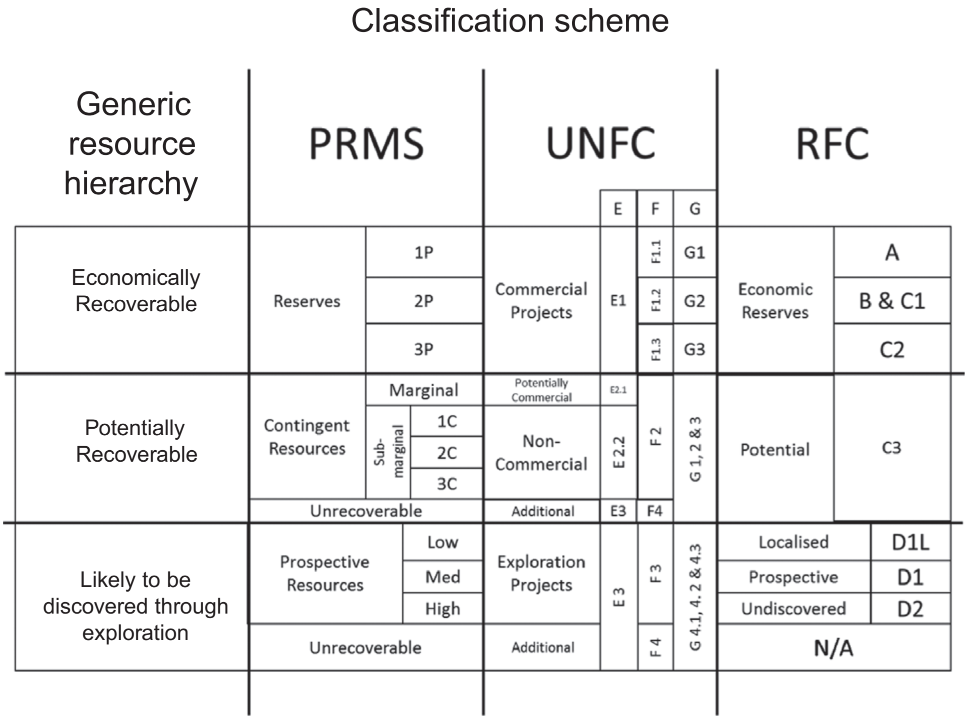


Fig. 4. Comparison of three reserve and resource classification schemes: the SPE/PRMS, the UNFC (2009), and the Russian Federation Classification.

technologies can be applied, this estimate is often called the *technically recoverable resource*. While if it is assumed that future technologies can be applied (which either lower extraction costs or increase potentially producible quantities) the resource estimate is often called the *ultimately recoverable resource*.

Finally, a proportion of the total commodity initially in place is unlikely to be produced due to physical challenges associated with its extraction, and the resulting costs. This may be referred to as *additional quantities in place* or *not recoverable*.

An approximate comparison of the different categorisations used in the PRMS, UNFC, and Russian Federation Classification (RFC) schemes, and how these compare with the generic resource hierarchy, is presented in Fig. 4. Because the exact definitions used in these schemes are not directly equivalent there may be a material impact, not just on the nomenclature, but on the quantitative estimates produced using these systems. Combining reserve estimates from different classification schemes will therefore introduce errors into aggregate reserve estimates. This has implications for global fossil fuel reserve estimates, which are inevitably complied from a range of differing classification schemes. These errors correspond to the 'knowledge of probabilities' axis in Fig. 2, and are difficult to reduce given the available information.

In addition to the reserves and resources categories described above, fossil fuels may also be classified according to the properties of the commodity produced, the technologies used to produce it, or the geological properties of where it is located (e.g. *'conventional'* vs. *'unconventional'* oil (Sorrell et al., 2010)). There is no agreed definition of these terms and this can lead to confusion resulting from different authors: (a) using the same term to mean different things; (b) using different terms to mean the same thing; or (c) applying different assumptions in the derivation of otherwise identical terms. In general, however, the more disaggregated the resource categorisation, the easier it is to examine and characterise the uncertainties embodied within it (Mcglade, 2012). The lesson for policy makers is that caution is needed, particularly when debating global figures for resource availability, such as those produced by the IEA.

4. Fossil fuel resources – sources of uncertainty

Knowledge of the uncertainties affecting fossil fuel resource estimates usually depends on the production history of the resource. To illustrate the range of uncertainties that can arise we contrast estimates for oil (be they 'conventional'[4] or 'unconventional') reserves and shale gas resources. Production of these resources is at very different stages of historical maturity, leading to significant differences in the level and nature of resource uncertainty. It is also important to note that sustainability criteria have, to date, rarely if ever been considered as part of the fossil fuel reserve or resource estimation process.

4.1. Oil reserves

When estimating reserves it is impossible to have complete knowledge of all 'below-ground' factors. This epistemic uncertainty is a normal feature of any reservoir evaluation and is why reserves classifications are given with varying levels of confidence (*1P*, *2P* and *3P*) as discussed above.

A key issue with examining aggregate reserve estimates, particularly at the global level, is the need to rely, at least to some extent, on data from incommensurable reporting sources, such as BP (2013), the Oil and Gas Journal (Xu and Bell, 2013), and OPEC (2012). These vary significantly in their availability, scope, quality and reliability in addition to the classifications and categorisation differences described above. Few of these sources explicitly clarify the exact meaning of terms used, with many for example simply using the term 'crude oil' or 'conventional oil' but not explaining which liquids are included within this.

The extent to which estimates correspond to the stated definition can also cause problems. For example, the statistical nature

---

[4] For the avoidance of doubt, here we use the term 'conventional oil' to mean all oil that is less dense than water (frequently given as $>10^{o}$API) when found in its native state, regardless of production technology, geographic location, or geological formation in which it is found.

of aggregating probabilistic reserve estimates is frequently ignored. A *1P* or P90 reserve estimate of individual fields within a country cannot simply be arithmetically summed to give an aggregate *1P* or *P*90 estimate for that country (Pike, 2006). Doing so, would likely result in a systematic underestimation of the true aggregate *1P* estimate (Sorrell et al., 2010).[5]

A further problem is the extent to which uneconomic or ‘stranded’ oil is included in reserve data. Most sources agree that volumes should be considered as reserves only if they are technically and economically producible within a ‘reasonable timeframe’ (as noted in Section 3 above). Yet some volumes that do not satisfy these criteria are still included in reserve data. For example, BP (2013) indicates there are 175 Gb and 298 Gb of Canadian bitumen and Venezuelan extra-heavy oil. These are vast numbers, but they will not be produced within the next (say) 30 years even under the most optimistic projections for production increases and so they would be better considered as potentially recoverable resources rather than as reserves.

Reserve estimates also have an important political dimension, leading to the notion of *political reserves*. These are volumes of oil declared by a country or company that do not correspond to the reserves it possesses but rather those which it would like to convey to the rest of the world (Laherrere, 2006). There has been an extensive debate regarding whether the reserves of several OPEC countries should be considered ‘real’ or ‘political’ (see e.g. (Owen et al., 2010)). The declared *1P* reserves of Kuwait are frequently questioned in this regard. The OPEC Statistical Bulletin (OPEC, 2012) reports these to be 101.5 Gb (having been at exactly this level since 2004), yet Schindler and Zitell (2008) and Campbell and Heapes (2009) report that Kuwait's *2P* reserves, which by definition should be higher than *1P* reserves, are closer to 50 Gb. I.e. there is a discrepancy of over 50 Gb.

Analysts tackle the possibility of politically motivated reserve inflation by OPEC in different ways. Some say that OPEC reserves are significantly overestimated and so discount them to a large extent, for example Owen et al. (2010) reduce OPEC's claimed reserves by around 300 Gb and Campbell and Heapes (2009) remove around 110 Gb from Saudi Arabian reserves; however others take them at face value (e.g. Watkins (2006)). It is worth noting that any potential overestimation of reserves for this reason may to some extent cancel out the potential for underestimation that is associated with aggregating *1P* reserve estimates, discussed above. Regardless, this political dimension results in significant gaps in knowledge, which in terms of the knowledge matrix in Fig. 2 might be considered as a source of *ambiguity*.

A final gap in knowledge (*ambiguity*) for oil reserves, which has received more attention recently, is the volume of oil that can truly be considered reserves if stated political goals to limit CO_2 emissions are to be met (McGlade and Ekins, 2014, Meinshausen et al., 2009). The volume of oil that could be used if there is to be a reasonable chance of limiting the average surface temperature rise to 2° C – which might be termed ‘*sustainable reserves*’ – is likely much less than the volume of available reserves in a world with no carbon targets.

Mapping oil resource classifications onto the Fig. 2 matrix highlights how the nature of uncertainties changes for each resource category. Because oil reserves (1P, 2P, 3P) are comparatively well understood they are mapped to the ‘Risk’ quadrant reflecting the expectation that they are technically recoverable and that we can have some confidence about the social and political conditions that will permit recovery. *Potentially recoverable* resources are both less certain in terms of their technically recoverability and the increasing socio-political constraints on increasing fossil fuel exploitation and so would generally be located further to the right and below reserves on the matrix. Finally, *undiscovered resources* are mapped further towards the ‘ignorance’ quadrant as they are subject to greater uncertainty in both dimensions.

From the discussion above, however, it is evident that the confidence we can have in both of these dimensions will vary from country to country. Mapping reserve estimate for individual countries would yield a useful, albeit qualitative, comparison of how they are affected by different types of uncertainty. In this way the matrix could also be used as a tool for expert elicitation and synthesis.

4.2. Shale gas resources

Shale gas is a topical example of one of a number of fossil fuel resources for which there is far less empirical evidence on which to base reserve estimates than for conventional oil – other examples include tight oil, kerogen oil and tight gas. Analysts, therefore, often focus on calculating less constrained quantities such as the technically recoverable resource (see Section 3 above). The principal sources of uncertainty derive from three main causes: (i) inconsistent definitions; (ii) limited data availability; and (iii) problems with the methods used to generate resource estimates (McGlade et al., 2013a, 2013b).

Definitional uncertainty can arise from the continued use of terms much more appropriate to conventional gas resource estimates. The United States Geological Survey (USGS), for example, often uses the term *’undiscovered’* shale gas (Coleman et al., 2011). But because shale gas is found in continuous formations, the location and boundaries of which are usually well-known, the term ‘*potential additions to reserves*’ (i.e.: resources minus reserves) would arguably cause less confusion (Charpentier and Cook, 2010).

The absence of any significant drilling experience for many regions of the world also means that current resource estimates are not necessarily well founded. For some regions there may only be a single estimate, and for some countries no contemporary estimates have been made at all.

Methodologically, new estimates of shale gas resources are usually generated in one of two ways: bottom up analysis of geological parameters, or the extrapolation of experience obtained from other areas of shale gas production. Both of these approaches are extremely sensitive to variations in single modelling parameters: in particular the recovery factor applied with the geological approach and the assumed functional form of the production decline curve for individual wells with the extrapolation approach. Both of these parameters are currently poorly understood with regard to shale gas production and remain hotly contested (McGlade et al., 2013a, 2013b).

Mapping of shale gas resources onto the Fig. 2 matrix needs to reflect the fact that: (i) the physical, technical and economic uncertainties are greater, and (ii) the sustainability (e.g. water availability) and socio-political (e.g. public opposition) uncertainties are both already impacting on the estimation of resources. The resulting diagram would be similar to Fig. 5 but with each of the categories shifted towards the bottom and right of the matrix.

5. Critical metal resources

A number of metals are expected to become increasingly sought after as demand for low carbon technologies increases (Speirs et al., 2011, 2013b, 2013c). This has led to increasing

---

[5] For example, if a country contains only two fields that each contain 5 Gb *1P* reserves, it would likely be incorrect to say that the *1P* reserves of that country is 10 Gb (5 Gb+5 Gb). The true *1P* reserve estimate for the country would depend on the shapes of the reserve estimate distributions for each of the fields and the correlation between them.

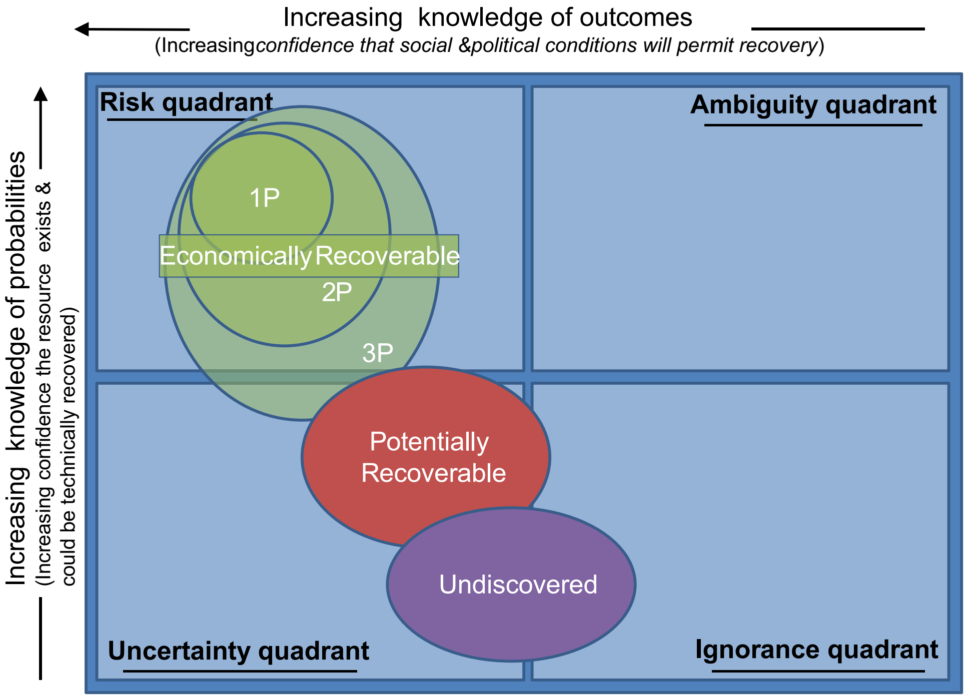


Fig. 5. Mapping oil resource classifications to contrasting states of incomplete knowledge.

concern over their future availability and their potential to constrain deployment rates for low carbon technology.

Metal resources are similar to fossil fuel resources in several ways. First, they are recovered from deposits in the earth's crust where geological processes have concentrated them. Second, they are non-renewable, so as the most accessible deposits are exhausted, mining companies must move to less accessible and poorer quality deposits that are harder and more expensive to extract. Finally, some quantities of metals in the earth's crust are considered unrecoverable in commonly used classification schemes (Henley and Allington, 2012). These similarities mean that metal resources are commonly reported in a similar way to fossil fuel, and using similar definitions.

Metal resources, however, differ from fossil fuel resources in two important ways. First, they are largely recyclable as uses of metal tend not to be destructive (Reck and Graedel, 2012). Second, many of the scarce metals used in low carbon energy technologies, the so called *critical metals*, are extracted exclusively as by-products of refining processes for base metals such as copper or zinc. This complicates the economics of their recovery and impacts on the uncertainty surrounding their future availability. If by-products are produced above the natural equilibrium level of demand this may also distort metal markets, decreasing prices and affecting price sensitive aspects of their resource systems, such as end-of-life recycling.

Given the similarities between critical metals and fossil fuels many of the same drivers of uncertainty in resource estimation exist, including limitations in the available physical data. As with oil reserve estimation, this uncertainty is captured in the reserve classification schemes. However, the granularity of *1P*, *2P* and *3P* probabilistic estimates applied to oil is not commonly available for metals. Instead, publically available reserve estimates tend to report a single figure. Until 2010 the United States Geological Survey (USGS) also provided estimates of the '*reserve base*', which included an estimate of all currently economically producible reserves, and other resources having "…a reasonable potential for becoming economically available within planning horizons…." This provides a slightly wider range of estimates on which to base judgments of uncertainty, though there is no probabilistic aspect to these estimates.

Because many of the factors driving demand for critical metals are comparatively new, the more sophisticated resources assessment techniques applied to fossil fuel resources have yet to be applied. Given the fundamentally conservative nature of existing estimates, it is reasonable to expect that both future discovery and reserve growth will add to overall reserve estimates. If the demand for and economic importance of these metals increases as expected then the incentive to study critical metal resources in terms of their undiscovered resources and reserve growth will also increase. Nevertheless, at the present time there is only limited evidence on which to base estimates of what is ultimately producible.

The reliance on relatively few sources of data presents a significant problem with the vast majority of studies relying solely upon the USGS (Speirs et al., 2013c). This data set is compiled from several international and commercial sources, often with differences in their estimation methods, which introduces further uncertainties. Other source data is available but is only used in a few studies, tends to cover fewer metals, and is updated less frequently (Candelise et al., 2011; Crowson, 2001). This situation may improve as the economic importance of these metals increases.

Increasingly, the environmental implications of extractive industries are being examined by NGOs, regulators and policy makers. However, estimating the impact of sustainability constraints on resource estimates is a difficult exercise given the political and social dimensions of environmental regulation. Techniques used to assess such limitations include qualitative scoring, life cycle analysis, and metrics compiled by independent third parties. However, the true quantitative impact on reserve and resource estimates of environmental issues is not well understood.

Critical metals also differ from fossil fuels in the fact that they are recovered as by-products from refining other metals. For example, tellurium and selenium are almost exclusively recovered as a by-product of copper refining, indium is almost exclusively recovered as a by-product of zinc refining, and the platinum group metals may be recovered together from a single ore body (as may other rare earth metals). This means that metal supply does not just respond to the current price of the by-product metal, but also to the price of the host metal. This relationship between by-product and host metals impacts on the estimation of resources. For example, the USGS estimates the tellurium resource by assuming a recoverable proportion of the total tellurium associated with estimated copper reserves. However, opportunities also exist to recover tellurium from ores of other base metals, or to recover tellurium from some ores in its own right. If these types of projects proceed, tellurium reserve estimates might increase significantly.

Another significant uncertainty in future metal availability not mirrored in fossil fuels is the fact that metals may be recycled. The implications of recycling on future availability are difficult to quantify for the following reasons. First, estimates depend on assumptions regarding the product lifetime. If all of the critical metals produced today are used as components for technologies with a life span of 20 years then access to these metals will be delayed by this 20 year period. Second, the recycling rate (the ratio of recovered metal to total metal in a product) is often not known, although it will always be less than 100%. Finally, the proportionate contribution that recycling can make to production is likely to diminish in periods when production is growing most rapidly. I.e. during periods of rapid growth, recycling will be limited in its relative capacity to contribute to supply. This 'high demand growth' scenario is likely to be the case for many of the critical metals in the coming decades. The impact of recycling has been explored by a number of authors, but a robust and accepted understanding of the future potential of recycling does not yet exist (Houari et al., 2013; Fthenakis, 2009).

Expressed in terms of the Fig. 2 matrix, it is apparent that there is a greater level of *ignorance* about critical metals than for fossil fuels, but it clearly makes limited sense to try to evaluate and communicate the nature of these uncertainties for critical metals as an aggregate group. A more disaggregated approach would be required.

6. Biomass resources

Biomass resource estimates differ from fossil fuels and metals in a number of important ways:

- Biomass is a renewable resource that can be produced in perpetuity provided soil fertility is maintained and water resources conserved. The size of the resource therefore depends on the timeframe considered, and the resource may be modelled as a continuous flow rather than a depleting stock.
- There are complex interactions between biomass production and alternative land uses. This gives rise to potential conflicts between biomass production, food, wood and paper production, biodiversity conservation, and urbanisation.
- Compared with oil fields or mines, biomass is a geographically dispersed resource. The amount of biomass varies according to the productivity of land but is always proportionate to the area from which it is harvested. The consequence of this is that the direct and indirect impacts associated with biomass production are diffuse and difficult to quantify.
- Biomass resources include a diverse range of feedstocks, including dedicated energy crops, residues from agriculture and forestry, and both wet and dry waste materials. Conversion to high quality energy services necessitates a portfolio of conversion technologies, some of which are still pre-commercial. The development of the biomass resource is thus intertwined with expectations regarding technological advancement.

Biomass resource estimates are also derived from models rather than from extrapolating current experience. Models vary in sophistication, but all aim to integrate information from sources such as the Food and Agriculture Organisation's (FAO) databases, field trials, satellite imaging data, and demand predictions for energy, food, timber and other land-based products, to elucidate bioenergy's future role. The least complex approaches use simple rules and judgment to estimate the future share of land and residue streams available for bioenergy. The most complex use integrated assessment models which allow multiple variables and trade-offs to be analysed.

In all cases the future supply of biomass depends on the availability (and productivity) of land for energy crops, and the accessibility of residues and wastes. The future evolution of these factors depends, in turn, on:

- Global population growth.
- Per capita food consumption and diet (a vegetarian diet requires less land than one rich in meat and dairy).
- The potential to increase crop yields, and to close the gap between optimal yields and those achieved by farmers (increasing yields may also have energy, water, and cost implications).
- Water availability, the impacts of climate change on productivity, nutrient availability and soil degradation.
- The area set aside for nature conservation (Thrän et al., 2010) (Berndes et al. 2003) (Lysen et al., 2008).

The major uncertainties in estimates of biomass potential reflect differing judgements of the relative importance of these factors and differing expectations for how they may evolve over time.

Like fossil fuels, biomass resources are most often discussed in terms of a hierarchy of potentials, the most commonly used categories being: *theoretical*; *technical/geographic*; *economic* ; and *realistic/implementable*.[6] These categories are not defined as precisely as those for fossil fuels and, because there are very few projects from which data can be aggregated, estimates tend to be derived from comparatively simple top-down projections. A *'theoretical'* estimate, for instance, might be calculated by assuming that all global terrestrial net primary productivity (NPP) not needed for food could be available for bio-energy purposes. Although global NPP can be estimated reasonably precisely using satellite imaging methods (see for example: Haberl et al. (2013) and Krausmann et al. (2007)), the proportion of global NPP which is dedicated to food production is difficult to determine. Such calculations tend to result in large and abstract biomass potential estimates that resemble the "total commodity originally in place" category used for fossil fuels and metals. At the other end of the hierarchy, an economic potential could be estimated by constraining the quantity of biomass to an amount that could be produced at a specific price within specific sustainability criteria. This would lead to a much smaller number that was arguably of greater use to policy makers, but also one that was inherently more subjective. The uncertainty in these estimates is not as a result of a lack of knowledge about net photosynthesis in different parts of the world, but rather comes from uncertainty around the normative social and environmental sustainability constraints that are embodied in their derivation. In terms of the Fig. 2 matrix, the results can be characterised as highly ambiguous.

---

[6] A recently mooted modification to the hierarchy of potentials has been the inclusion of a sustainable potential category, defined as: *"the fraction of the technical biomass potential which can be developed in a way which does not oppose the general principles of sustainable development, i.e. the fraction that can be tapped in an economically viable manner without causing social or ecological damage"* (BEE, 2008) (Vis and Van Den Berg, 2010). This idea was proposed in an attempt to improve the comparability of biomass resource assessments by harmonising assessment methods and clearly illustrates the importance of normative decisions in defining resource potentials.

In its 2011 Special Report on renewable energy sources, the Intergovernmental Panel on Climate Change (IPCC) concluded from a review of the available literature that the technical potential of biomass depends on “factors that are inherently uncertain” and cannot be determined precisely while societal preferences are unclear. With these caveats in mind, the IPCC authors concluded that by 2050 biomass deployment of could reach 100-300 EJ (cf. current global primary energy supply of ~550EJ). They emphasise, however, that biomass use could evolve in a sustainable or unsustainable way and to pursue a sustainable trajectory it would be necessary for land use to be governed effectively, for agricultural and forestry yields to be increased and for competing demands for food and fibre to be moderate (IPCC, 2011). The biomass resource assessments which underpin this recommendation, however, provide limited insight into the level of deployment that might be achievable in practice. Rather, they describe scenarios in which biomass makes an increasing contribution to primary energy supply while attempting to minimise the negative impacts by imposing environmental constraints on deployment. They are systematically optimistic in the sense that they try to identify the least damaging land allocations that permit more biomass production. They are not forecasts extrapolated from empirical observations or any practical experience of trying to achieve large scale transitions in energy crop production, or residue use at a global scale. Nor do they try and predict the land allocations likely to result from current or future demand. This is not always apparent from the way in which modelling results are described, interpreted, or used to justify policy interventions (Slade et al., 2014, 2011b). It also means that they are incommensurate with reserve estimates for fossil fuels and metals and are of limited use to investors.

To overcome these limitations, recent attempts have been made to introduce bottom-up resource estimation methodologies. These aim to characterise existing and planned bioenergy projects according to their future cumulative energy output bounded by technological constraints and assuming a standard economic lifetime for a project. By considering a project’s commercial status within these constraints, it is possible to evaluate the cumulative energy output over the project lifetime, and to classify this output as a reserve analogous to *1P* oil reserves (Turner et al., 2013). The rationale behind this approach is that biomass and fossil fuels can be considered equivalent in a number of respects, including that: a biomass or fossil fuel project has a fixed level of investment, with an expected production profile; they both progress through stages of a production cycle; they have similar prerequisites such as gaining access to the resource and market, receiving authorisation, and validation of the economic case; and, as the project develops, risk declines and certainty of returns improves.

In their attempt to develop a renewable resource estimation methodology, Bloomberg New Energy Finance consider the asset lifetime for biomass projects to be 30 years, with estimates of reserves and resources being calculated based on the cumulative production potential over that period (Turner et al., 2013). An argument against this approach is that project lifetimes are likely to be highly variable and case specific. Another area of debate is the point in the fuel chain at which biomass resources are measured (Primrose and Dolle, 2014). For instance, the capacity of a biomass project may be measured as the total energy content of the feedstock, or the energy content of the products (i.e. biofuel, wood pellets, electricity, etc.). However, the energy value measured at these two points may be quite different depending on the end-use product being manufactured and the efficiency of the conversion process. The fact that many biomass fuel chains use co-products from other system as feedstock (e.g. wheat straw) and yield large quantities of co-products in addition to energy may further complicate the calculation. Oil resources are traditionally measured in barrels of crude oil, not as the end-use product (i.e. diesel, petrol etc.), and biomass resources could in principle be measured in the same way using the energy content of the feedstock. Yet, differences in feedstock type, quality, and moisture content would again lead to a wide range of values. For these reasons resource estimates based on the energy content of the final product may better reflect the energy resource of a bioenergy project and the net energy yield of the fuel chain. The UNFC appear to be following the latter, end-use product, approach to biomass resource estimates though their methodology is not yet finalised (Primrose and Dolle, 2014).

Assessing biomass resources and traditional energy resources under a common classification system may yield several benefits. Owners of renewable resources will gain: an enhanced overview of asset values; a measure of comparability with traditional energy systems; a basis to estimate the scale of each renewable resource; and reliable estimates based on best practices and common standards. External stakeholders such as investors, governments and international organisations may also benefit. Fair comparison between different energy resources could also improve the assessment of different investment opportunities and enhance portfolio valuation. The total resource base would also be easier to assess which could help inform integrated energy strategies and policies.

A way in which bioenergy resource estimates might be mapped to the Fig. 2 matrix is shown in Fig. 6. For bioenergy products that are already widely available (for example bioethanol and biodiesel) there is a good understanding of the probability that a new biofuel project will deliver the anticipated quantity of fuel. The challenge is that dedicating land to these energy sources has become increasingly socially unacceptable, thus the realistic/implementable biomass resource would arguably lie further towards the ambiguity quadrant than 1P/2P estimates for conventional oil resources. Theoretical biomass potentials can be quantified from global sensing data (i.e. there is a good level of knowledge that the resource exists) but they are also associated with a high level of ambiguity because the potential consequences of developing these resources are untested. Unlike fossil fuels there are no biomass resources that are *undiscovered*.

7. Conclusions and policy implications

This paper examines how resource estimates for fossil fuel, critical metal and biomass are conceptualised in terms of a hierarchy of availability, and explores the uncertainties associated with these estimates using a descriptive typology, and a conceptual matrix that characterises uncertainty as contrasting states of incomplete knowledge.

The best developed and most mature methods for categorising resource availability are those developed for fossil fuels. Methods used for critical metals and biomass adopt a similar hierarchical approach, but tend to be simpler, reflecting more limited available data, and smaller market size.

For all these resources, however, we find that data limitations, inconsistent definitions and the use of incommensurable methodologies present a pervasive problem, impeding the comparison of dissimilar resource types. These limitations need to be recognised when developing and comparing aggregate resource estimates and when using these to inform strategic energy policy decisions.

Particular caution is required when comparing estimates for similar resources at different levels of the resource classification hierarchy. For instance, estimates for shale gas and biomass resources embody far greater uncertainties that those for conventional fossil fuels. This uncertainty needs to be acknowledged in

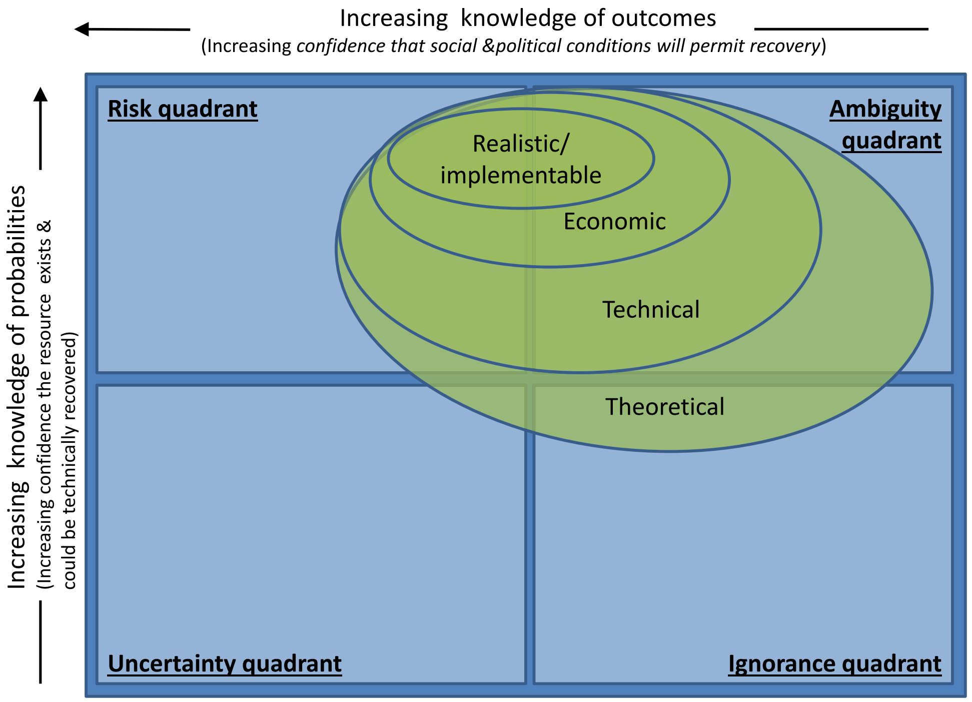


Fig. 6. Mapping biomass resource classifications to contrasting states of incomplete knowledge.

the political debate about the merits and limitations of including these resources in future energy scenarios.

Comparing depleting stocks of minerals with the potentially inexhaustible flow of renewable resources can also be problematic. The development of appropriate methodologies to achieve this is remains an area of active research, but, once adopted, a common classification system may aid fair comparison between different energy resources and their integration into energy strategies and policies.

Reducing uncertainties almost inevitably involves trade-off. The physical uncertainty around the European potential for shale gas, for example, could be reduced by increasing the number of shale gas wells drilled. This increased physical knowledge, however, may come at the cost of increased socio-political uncertainty by inciting public opposition. The backlash against biofuels produced from food crops provides a salutary example of how rapidly such opposition can arise.

The uncertainties associated with resource availability can themselves be identified and categorised according to their origin – e.g. as physical, economic, technical, political etc. This, essentially reductionist, approach helps identify the root causes of many uncertainties and results in a descriptive list of where uncertainties arise. Comparing this typology with established resource classification schemes highlights the fact that many aspects of resource uncertainty are not commonly captured, easy to describe, or quantified in the conventional schemes.

The knowledge matrix is an alternative approach to conceptualising uncertainty that draws on a constructivist epistemological tradition. To apply this matrix to we found it necessary to interpret the axes in terms of the *confidence about whether a resource exists* and *confidence about the social and political condition that will permit recovery*. In this form the matrix highlights that many of the uncertainties surrounding resource estimates reflect divergent social values and perspectives. It also highlights dynamic nature of these uncertainties, and as investments are made, as new evidence emerges, and as technology advances the position of a resource on this matrix will change. As a qualitative framework, the matrix has potential to be used as an expert elicitation tool, likely be most applicable to understanding the possible dynamics for the resource held by a specific licence holder or an individual resource in a given country. If applied at too aggregated a level, the array of physical, economic, technical, political uncertainties affecting the resource would simply traverse all of the knowledge quadrants.

Fossil fuels, critical metals, and biomass are clearly affected by multiple uncertainties in ways that reflect the origin, processing and political economy of these resources. Communicating the implications of these uncertainties is challenging, particularly when they fall beyond the range of conventional risk assessment, and classification approaches. In this context, both the risk typology and the knowledge matrix approaches have the potential to be useful analytical and communication tools. Sources of uncertainty cannot be eliminated, but as the discussion in this paper shows, a better understanding of *how*, *why*, and *where* uncertainty arises is essential for an informed policy debate.

Acknowledgements

This research undertaken as part of the UK Energy Research Centre (UKERC) project: Energy Strategy Under Uncertainties. We gratefully acknowledge the advice and guidance provided by Rob Gross, Andrew Lovett, Steve Sorrell, Jim Watson and the rest of the UKERC team.

References

ARI, 2013. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. Advanced Resources International Inc, Washington, DC.

BEE, 2008. Status of biomass resource assessments — version 1: a report for the Biomass Energy Europe (BEE) project — FP7 Grant Agreement 213417. IFEU.

Berndes, G., et al., 2003. The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenerg. 25, 1–28.

BP, 2013. BP statistical review of world energy.

Campbell, C.J., Heapes, S., 2009. An Atlas of Oil and Gas Depletion. Huddersfield. Jeremy Mills, West Yorkshire [England].

Candelise, C., et al., 2011. Materials availability for thin film (TF) PV technologies development: a real concern? Renew. Sustainable Energy Rev. 15, 4972–4981.

Charpentier, R.R., Cook, T.A., 2010. Improved USGS Methodology for Assessing Continuous Petroleum Resources. United States Geological Service, Reston, VA.

Coleman, J.L., et al., 2011. Assessment of Undiscovered Oil and Gas Resources of the Devonian Marcellus shale of the Appalachian Basin Province. US Geological Survey, Reston, VA 2011.

Crowson, P.C.F., 2001. Minerals Handbook 2000–01 Statistics & Analyses of the World's Minerals Industry. Mining Journal Books, Endenbridge.

DTI, 2007. UK Biomass strategy 2007: Working Paper 1 – Economic Analysis of Biomass Energy. Department of trade and industry: Energy technologies unit.

Eide, A., 2008. The Right to Food and the Impact of Liquid Biofuels (agrofuels). Rome. Food and Agriculture Organization of the United Nations, Rome.

Fthenakis, V., 2009. Sustainability of photovoltaics: the case for thin-film solar cells. Renew. Sustainable Energy Rev. 13, 2746–2750.

Haberl, H., et al., 2013. Bioenergy: how much can we expect for 2050? Environ. Res. Lett. 8, 1–5.

Hayes-Labruto, L., et al., 2013. Contrasting perspectives on China's rare earths policies: reframing the debate through a stakeholder lens. Energy Policy 63, 55–68.

Helm, D., 2011. Peak oil and energy policy—a critique. Oxford Rev. Econ. Policy 27, 68–91.

Henley, S. and Allington, R. 2012. Reserves classification systems around the world [Internet], Pan-European Reserves and Resources Reporting Committee, available from: 〈http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/eu-us-henley_en.pdf〉 (accessed: 13.12.2013).

Houari, Y., et al. 2013. A system dynamics model of tellurium availability for CdTe PV. Prog. Photovoltaics: Res. Applications, n/a-n/a.

IIASA, 2012. Global Energy Assessment—Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA, and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

IPCC, 2011. Bioenergy IN IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Krausmann, F., et al. 2007. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. Ecological Economics.

Laherrere, J. 2006. Oil and gas: what future? Groningen.

Leaton, J., 2011. Unburnable Carbon—are the World's Financial Markets Carrying a Carbon Bubble?. Investor Watch, London, UK.

Lynd, L. R., et al. 2011. A Global Conversation About Energy From Biomass: The Continental Conventions of the Global Sustainable Bioenergy project. Interface Focus.

Lysen, E., et al. 2008. Biomass Assessment: assessment of Global Biomass Potentials and their Links to Food, Water, Biodiversity, Energy Demand and Economy. Netherlands Environmental Assessment Agency MNP.

Maugeri, L., 2009. Understanding oil price behavior through an analysis of a crisis. Rev. Environ. Econ. Policy 3, 147–166.

McGlade, C., 2012. A review of the uncertainties in estimates of global oil resources. Energy 47, 262–270.

McGlade, C., Ekins, P., 2014. Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system. Energy Policy 64, 102–112.

McGlade, C., et al., 2013a. Methods of estimating shale gas resources – Comparison, evaluation and implications. Energy 59, 116–125.

McGlade, C., et al., 2013b. Unconventional gas – a review of regional and global resource estimates. Energy 55, 571–584.

Meinshausen, M., et al., 2009. Greenhouse gas emission targets for limiting global warming to 2° C. Nature 458, 1158–1162.

Moss, R.L., et al., 2011. Critical Metals in Strategic Energy Technologies. European Commission Joint Research Centre (EC JRC), Brussels, Belgium.

OPEC 2012. Annual Statistical Bulletin. Vienna, Austria, Organization of the Petroleum Exporting Countries.

Owen, N.A., et al., 2010. The status of conventional world oil reserves—Hype or cause for concern? Energy Policy 38, 4743–4749.

Pearson, I., et al., 2012. Unconventional Gas: Potential Energy Market Impacts in the European Union, Joint Research Centre, Institute for Energy and Transport. European Commission.

Pike, R. (2006). Have we underestimated the environmental challenge. Petroleum review, June, 26–27.

Primrose, J., Dolle, N., 2014. Application of the UNFC-2009 to Renewable Energy Resources "The Concept". UNECE Workshop on Application of UNFC to Renewable Energy hosted by the World Bank. Washington.

Reck, B.K., Graedel, T.E., 2012. Challenges in Metal Recycling. Science 337, 690–695.

Schindler, J., Zitell, W., 2008. Crude Oil: The Supply Outlook. Energy Watch Group, Berlin, Germany.

SEC, 2008. Modernization of the Oil and Gas Reporting Requirements. Conforming version (proposed rule) [Internet], available from: 〈http://www.sec.gov/rules/proposed/2008/33-8935.pdf〉 [Accessed: 17 CFR Parts 210, 229, and 249 [Release Nos. 33-8935; 34-58030; File No. S7-15-08]].

Slade, R., et al., 2014. Global bioenergy resources. Nature Climate Change, 99–105.

Slade, R., et al., 2011a. Estimating bio-energy resource potentials to 2050: learning from experience. Energy. Environ. Sci., 2645–2657.

Slade, R., et al., 2011b. Energy from biomass: the size of the global resource. Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London, UK.

Sorrell, S., et al., 2010. Global oil depletion: a review of the evidence. Energy Policy 38, 5290–5295.

Spe, et al. 2008. Petroleum resources management system.

Speirs, J., et al., 2013a. Energy Materials Availability Handbook. UK Energy Research Centre, London.

Speirs, J., et al., 2011. Materials Availability: Potential constraints to the future low-carbon economy. Working Paper I: A thin film PV case study. UK Energy Research Centre, London.

Speirs, J., et al., 2013b. Materials Availability: Materials Availability: Materials Availability: Materials Availability: Potential constraints to the future low-carbon economy. Working Paper II: Batteries, Magnets and Materials. UK Energy Reseach Centre, London.

Speirs, J., et al., 2013c. Materials Availability: Comparison of Material Criticality Studies—Methodologies and Results. Working paper III. UK Energy Research Centre, London.

Stirling, A., 2007. Risk, precaution and science: towards a more constructive policy debate. EMBO 8, 309.

Stirling, A., 2010. Keep it complex. Nature 468, 1029–1031.

Thrän, D., et al., 2010. Global biomass potentials—resources, drivers and scenario results. Energy Sustain. Dev. 14, 200–205.

Thunnissen, D. P. 2003. Uncertainty Classification for the Design and Development of Complex Systems. In: Proceedings of the 3rd Annual Predictive Methods Conference, Newport Beach, California.

Turner, G., et al. 2013. Renewable reserves: testing the concept for the US and Brazil (A report by Bloomberg New Energy Finance, commissioned by BP). New Energy Finance, London.

UKLA 2012. UK Listing Authority [Internet], available from: 〈http://www.fca.org.uk/firms/markets/ukla〉 (accessed: 12.12.2013).

UNFC 2009. United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources. United Nations Economic Commission for Europe.

Vis, M.W., Van Den Berg, D., 2010. Harmonization of biomass resource assessments (volume I) best practices and methods handbook. A report for the Biomass Energy Europe (BEE) project—FP7 Grant Agreement 213417.

Watkins, G.C.C., 2006. Oil scarcity: what have the past three decades revealed? Energy Policy 34, 508–514.

Xu, C., Bell, L., 2013. Worldwide reserves, oil production post modest rise. Oil Gas J. 111.