Resourcing Future Generations White Paper

Mineral Resources and Future Supply

October 2014

IUGS

International Union of Geological Sciences

RESOURCING FUTURE GENERATIONS

International Union of Geological Sciences

The International Union of Geological Sciences (IUGS) was formed in 1961 as the umbrella organisation to represent the geosciences globally. It is a non-political, non-governmental and not-for-profit organisation. With 121 national members, the Union aims to promote development of the Earth sciences through the support of broad-based scientific studies relevant to the entire Earth system; to apply the results of these and other studies to preserving Earth's natural environment, using all natural resources wisely and improving the prosperity of nations and the quality of human life; and to strengthen public awareness of geology and advance geological education in the widest sense. It is a constituent body of the International Council for Science (ICSU). Further information is available at iugs.org and http://www.icsu.org/about-icsu/about-us

Resourcing Future Generations (RFG) is an IUGS initiative aimed at meeting the multigenerational needs for raw materials, energy and water while ensuring social equity. To do that requires four fundamental actions by the geoscience community:

1) comprehensive evaluation and quantification of 21st century supply and demand;
2) enhanced understanding of the subsurface as it relates to resource deposits;
3) assessment of where new resources are likely to be found; and
4) building needed and advanced skills capacity, particularly in lesser developed nations, to discover and responsibly develop mineral resources.

The broad concept is that RFG will last about a decade and be an umbrella activity under which a range of new activities related to securing the raw materials, energy and water resources required by future generations can be developed, coordinated and funded. It will provide a bridge between industry, academia and national geological surveys, and other Unions within ICSU will be invited to participate.

About the Authors

Edmund Nickless, Executive Secretary, The Geological Society, London, UK
Andrew Bloodworth, Science Director for Minerals and Waste, British Geological Survey, Keyworth, Nottingham, UK
Larry Meinert, Program Coordinator Mineral Resources, United States Geological Survey, Reston, Virginia, US
Damien Giurco, Associate Professor, University of Technology, Sydney (UTS), Australia
Steve Mohr, Senior Research Consultant, Institute for Sustainable Futures, UTS, Sydney, Australia
Anna Littleboy, Program Leader: Resources, Community and the Environment, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Brisbane, Australia

CITATION

Nickless, E., Bloodworth, A., Meinert, L., Giurco, D., Mohr, S., Littleboy, A. Resourcing Future Generations White Paper: Mineral Resources and Future Supply. International Union of Geological Sciences. 2014.

ACKNOWLEDGEMENT

The authors wish to thank the reviewers from the IUGS New Activities Strategic Implementation Committee and Ian Lambert (former Secretary General IUGS) for specialist input to this paper

CONTENTS

SUMMARY **1**

1. INTRODUCTION **2**

1.1. Relationship to other RFG initiatives 2
1.2. Purpose of White Paper 3
1.3. Outline of document 3

2. RESOURCES AND RESERVES **4**

2.1. Definitions 4
2.2. Approaches to mineral resource estimation 4
2.3. Reserves 11
2.4. Comparison of approaches 13

3. MODELLING SUPPLY **15**

3.1. Approaches to economic scarcity of resources 15
3.2. Physical approaches to modelling supply 16
3.3. System dynamic models 18
3.4. Model comparison 19
3.5. A note on supply outlook and technology 19
3.6. Recycling and secondary sources 20

4. COMMODITY SUPPLY CASE STUDIES **22**

4.1. Introduction and model description 22
4.2. Model results – summary 25
4.3. Model results – coal, iron ore, copper, lithium, phosphorous, helium 27
4.4. Discussion 33

5. CONCLUDING DISCUSSION **34**

REFERENCES **65**

FIGURES

Figure 1: The relationship between mineral resources and reserves. Mineral reserves generally only represent a tiny fraction of resources. Resource base refers to the total amount of a mineral or metal in the Earth's crust. *'Modifying factors' include mining, processing, metallurgical, marketing, social, environmental, legal and governmental considerations. 4

Figure 2: Possible cumulative production over the life of a resource (overlaid on JORC). Whilst new technology or more favourable economic conditions (e.g. cheaper operating costs or higher commodity prices) can increase the total volume of economic resource which could be extracted, higher social, environmental and techno-economic pressures can also constrain total available resources (and production). (Mason et al 2013)........ 5

Figure 3: Flow chart illustrating multiple steps of USGS 3-part method for assessing undiscovered mineral resources (from Singer, 2007)........ 7

Figure 4: Boundary of permissive tract is drawn based upon known geology and analogy with the appropriate mineral deposit model (from Singer, 2007)........ 8

Figure 5: Tonnage distribution of porphyry Cu deposits. Each point represents a deposit and intercepts are at the 90th, 50th, and 10th percentile (from Singer, 2007). 9

Figure 6: Distribution of known and undiscovered copper in four of eleven assessed regions from the 2013 USGS global Cu assessment compared to 2010 world copper production and reserves (Edelstein, 2011, Johnson et al., 2014). 10

Figure 7: Change in reserve estimates for UK Coal over time (upper figure) overlaid with actual annual UK coal production in the lower figure (Rutledge, 2013) 12

Figure 8: Assumed production profile in the RP method........ 17

Figure 9: Various models fitted to UK coal production........ 17

Figure 10: The periodic table of global average recycled content (RC, the fraction of secondary [scrap] metal in the total metal input to metal production] for sixty metals. Uncoloured boxes indicate that no data or estimates were available or that the element was not addressed by the authors of the study (Graedel et al., 2011)........ 20

Figure 11: The idealised field and mine profiles. 22

Figure 12: The projected world population 24

Figure 13: Projections of various minerals production created by GeRS-DeMo. 26

Figure 14 Historic production of Chinese and Rest of World coal production 27

Figure 15: Projection of future copper production by ore type (Northey et al. 2014) 30

TABLES

Table 1: Comparison of USGS reserves for selected minerals (in thousand metric tonnes) from USGS Mineral Commodity Summaries 11

Table 2: Comparison of requirements and outputs of the various inventory and probabilistic methods for crustal resource estimation 13

Table 3: The advantages and disadvantages of different model types for modelling supply 19

Table 4: URR numbers used in the supply projections 25

Table 5: Coal URR estimate split by country 28

Table 6: Iron ore URR by country 29

Table 7: URR estimates for copper by country 30

Table 8: Phosphorus URR by country 31

Table 9: Lithium URR by country and basin 32

Table 10: Helium URR by country 33

SUMMARY

Demand for natural resources will continue to rise in the decades ahead, driven by resource-intensive development and consumption in countries across the globe. This will occur even as strategies to reduce consumption and improve recycling and substitution become further implemented. To meet this demand requires the discovery of new sources of good quality minerals which can be mined, as well as access to affordable energy and water. Declining rates of discovery of major new resources and the decreasing land area available as communities and conservation regions expand pose major challenges.

Resourcing Future Generations (RFG) in Theme 1 activities “will focus initially on comprehensive evaluation and quantification of 21st century supply and demand”. This White Paper contributes to this theme by describing current approaches to quantifying available resources and to projecting future supply. Several techniques are available to assist with planning for future resource availability. Many are currently in use to support investment decisions on the part of resource companies and/or development strategies in emerging economies. However, there are limitations with these techniques and underlying data which become significant as we seek to think further into the future beyond 2050. In summary:

- **resource/reserve estimation** techniques identify the resources that may be in the ground and how economically viable they would be to extract from the ground. However, they are reliant on geological data and understanding which is uncertain, variable and, in some parts of the world, sparse.
- **supply/demand modelling** tools predict the future requirement for and availability of different commodities under certain assumptions regarding population growth, economic development and consumption patterns. However, they do not explicitly address the dynamic nature of socio-economic factors that can be expressed as concern about the environment, cost of energy, social license to operate or conflict. In a changing world, these factors are likely to become increasingly signficant – if only as a cost to resource businesses worldwide.

The upshot of these limitations is that the tools which we use to drive business models and capital investment around the world may be conservative in their ability to ensure that, in the long term, our future generations have options for resourcing their future world.

A key consideration for identifying new resources is the need for enhanced information on surface and subsurface geology, as a basis for applying new concepts of natural resource potential, particularly in lesser developed nations which are under-explored because of limited infrastructure, governance, geological knowledge and trained workforce. Programs aimed at facilitating discovery of resources for future generations need to span the geosciences and be truly multidisciplinary.

Additionally, through significant involvement of economists and social scientists and with engagement of industry, academia and governments, RFG seeks to ask the challenging questions about the assumptions implicit in our supply/demand modelling. How might population and consumption change with new technology and with the emergence of new economies? What are the implications of either ubiquitous cheap energy or increasing energy costs on the economic viability of different deposits? How might supply patterns be disrupoted through widespread social conflict mediated through social media channels and new interconnected networks?

RFG seeks to act as an international ‘honest broker’, bringing together interested parties to improve the ability of low income nations to advance through creating world-class and regionally self-sufficient natural resource-based industries, while enhancing the positive perception of resource production activities.

This White Paper, first presented at China Mining, Tianjin, 20 to 23 October 2014, has been prepared to both inform and stimulate discussion, and to explore the degree of interest across industry and academe in working together to pose and then consider the questions that challenge “business as usual” for the long term.

1. INTRODUCTION

Although mineral resources are non-renewable and unevenly distributed, global supply has so far kept pace with demand. However, humankind is now moving into an era of unprecedented population growth and environmental change. Can the abundant mineral supply we have enjoyed be sustained as demand continues to rise and the need to mitigate and adapt to environmental change becomes more pressing?

The UN forecasts that global population will be 10.9 billion by 2050, an increase of 50% on current levels (United Nations, 2013). This major demographic change is likely to be accompanied by substantial growth rates in the emerging economies as their populations urbanise, overcome poverty and in turn, aspire to middle-class lifestyles and consumption patterns seen elsewhere in the world. Through its urbanisation from 1981–2010, China lifted 680 million people out of extreme poverty (The Economist, 2013). Looking ahead to 2050, China will have developed more than 200 cities with more than 1 million inhabitants (Woetzel et al, 2009).

Population increase and economic development will continue to drive mineral resource use on an upward trajectory. Global consumption of copper is estimated to rise from approximately 20 million tonnes in 2007 to over 32 Mt in 2025 (Ayres et al, 2011). Global production of platinum group elements increased by 113% between 1980 and 2008 (Bloodworth et al. 2010). Massive growth in the use of electric and hybrid vehicles will be accompanied by equally high levels of demand for the rare earth elements needed to manufacture their batteries and propulsion units.

1.1. RELATIONSHIP TO OTHER RFG INITIATIVES

The International Union of Geological Sciences believes that it is important to develop, with other interested parties, a major new initiative with the challenging long-term goal of ensuring a supply of mineral, energy and water resources for the global society for the next century.

This initiative – called *Resourcing Future Generations* (RFG; Lambert et al., 2013) – is a response to the recommendations of the IUGS 2012 Strategic Report and the final report of the Global Geoscience Initiative, both of which recognised that population growth and the aspirations of lesser developed nations mean a priority is to secure new mineral, energy and water resources for future generations, while meeting the environmental and social imperatives for sustainable development. It is intended to involve researchers, academics, government agencies and industry globally.

The Union has established a New Activities Strategic Implementation Committee (NASIC) to scope RFG and the roles of interested parties in more detail. NASIC recommended that the minerals component of RFG be developed under four principal themes:

> **Theme 1.** Comprehensive evaluation of future global mineral resources, demand and supply for selected commodities, to provide enhanced information on which commodities are of concern post 2030 (addressed in this document).
>
> **Theme 2.** Enhanced information on the geology of the uppermost crust, for more effective delineation of new mineral, energy and water resources, managing wastes and assessing environmental condition, particularly in lesser developed countries.
>
> **Theme 3.** Improved evaluations of resource potential, with emphasis on new mineral systems, regions that have not been comprehensively explored and sedimentary basins as repositories of mineral, energy and groundwater resources.
>
> **Theme 4.** Capacity building and socioeconomic considerations in the developing world. This major component of RFG is necessary for effective exploration and mining as well as for good governance and socioeconomic benefits.

This White Paper considers Theme 1 as the means for building the collaborations required to tackle the other themes.

1.2. PURPOSE OF WHITE PAPER

The primary purpose of this White Paper is to stimulate discussion among academia, industry, national geological surveys and research funders and to invite comment. The paper seeks to set out the issues focussed on resource/reserve estimation and supply/demand modelling and the uncertainties inherent in those methodologies. Are the tools which we use to drive business models and capital investment around the world conservative in their ability to ensure that, in the long term, our future generations have options for resourcing their future world? Is there a problem and, if so, what contribution can the geoscience community make, working with other disciplines to improve knowledge and understanding?

Please send you views to rfg@geolsoc.org.uk

1.3. OUTLINE OF DOCUMENT

This paper considers the current practice in estimating resource potential and modelling supply and demand. It then considers what this means in terms of peak minerals for a range of commodities

Accordingly, Chapter 2 reviews approaches to the regional, continental and global-scale estimation of mineral resources. It provides an overview of inventory-based estimates and contrasts these with estimates based on probabilistic methods. Both approaches have advantages and limitations which this document seeks to highlight. The review of resource estimation also looks at the importance of geological data and understanding in underpinning both methodologies. This section also briefly looks at reserves data and their limitations in providing a reliable estimation of remaining crustal stocks.

Chapter 3 reviews approaches to modelling the supply of minerals, including common time horizons for approaches to modelling the supply of minerals. This section also examines both economic and physical approaches to modelling supply, as well as the role of secondary stocks and production. Chapter 3 then illustrates projections of mineral supply based on physical stocks for selected commodities, namely: coal, iron ore, copper, phosphorous, lithium, helium.

The paper concludes by identifying points of agreement and dissent, prevailing themes and unanswered questions as a basis for informing discussion and future research which will also need to focus further on factors underlying future demand.

2. RESOURCES AND RESERVES

RESOURCES AND RESERVES OUTLINE

This section describes:
- definitions regarding resources and reserves (2.1)
- approaches to mineral resource estimation, based on (i) resource inventories and (ii) probabilistic analyses (2.2).
- the dynamic nature of reserves (2.3)

2.1. DEFINITIONS

A mineral 'resource' is a natural concentration of material in or on the Earth in such form and quantity that economic extraction of a commodity is potentially feasible (USGS 2013). Resources can be subdivided into different categories, reflecting the level of geological knowledge and associated confidence in their existence (Fig. 1). Reserves are that part of an 'identified' resource that could be economically extracted at the time of assessment (USGS 2013). Accordingly reserves are economic entities that represent only a very small proportion of the total amount of a mineral or metal in the Earth, sometimes referred to as the 'resource base' (Fig. 1).

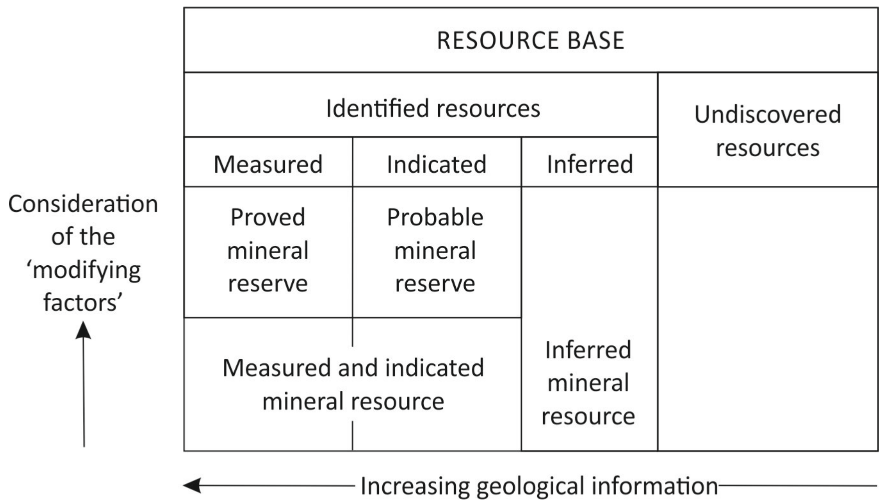


Figure 1: The relationship between mineral resources and reserves. Mineral reserves generally only represent a tiny fraction of resources. Resource base refers to the total amount of a mineral or metal in the Earth's crust. *'Modifying factors' include mining, processing, metallurgical, marketing, social, environmental, legal and governmental considerations.

2.2. APPROACHES TO MINERAL RESOURCE ESTIMATION

Two broad approaches have been used to quantify mineral resource endowment. The 'resource inventory' approach relies on compilation of data on known resources. The 'probabilistic' approach estimates the number of undiscovered mineral deposits that may be present within an identified area, along with their associated grade and tonnages.

2.2.1. Estimates based on resource inventories

Some of these inventories are compiled at a national level from data reported by companies, typically using an internationally-recognised code for reporting of mineral resources and reserves (such as JORC or PERC). Although subject to the inherent geological uncertainty associated with mineral resource estimation, the inventory will provide a good indication of resources available for extraction in the long-term. A good example of this approach is the annual national assessment of resources 'likely to be available for mining' published by the Australian federal government (Geoscience Australia, 2014). The Australian inventory does not take account of undiscovered resources, or include resources which are inaccessible for non-geological reasons (such as social and/ or environmental constraints, see Figure 2).

Other examples of resource inventories are global and compile publically available reserve information including company filings, annual reports, and websites. These typically include both reserves reported using internationally-recognised codes (such as JORC or PERC) as well as non-code information that is believed to be reliable. Such inventories have been done for cobalt (Mudd et al., 2013a), copper (Mudd et al., 2013b), nickel (Mudd and Jowitt, 2014), rare earth elements (Weng et al., 2014), and uranium (Mudd, 2014).

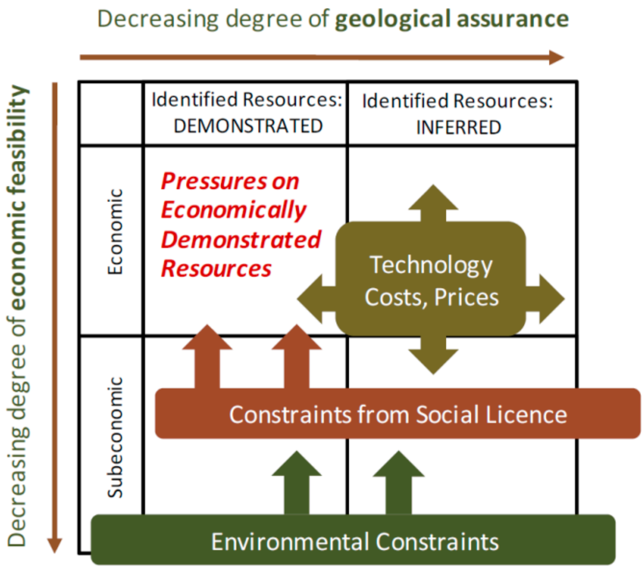


Figure 2: Possible cumulative production over the life of a resource (overlaid on JORC). Whilst new technology or more favourable economic conditions (e.g. cheaper operating costs or higher commodity prices) can increase the total volume of economic resource which could be extracted, higher social, environmental and techno-economic pressures can also constrain total available resources (and production). (Mason et al 2013).

Many (most) jurisdictions lack a policy framework which requires consistent mineral resource reporting standards and so resource inventory compilation can be more challenging. Ad hoc methods prevail which generally rely on estimates inferred from geological and mineral resource maps and models. These estimates may also take account of published and unpublished data from commercial, public sector and academic sources. Methods used will vary depending on the commodity type (from metallic minerals through to construction aggregates) and its host geology, as will the level of uncertainty attached to the estimates obtained. For example, the approach and uncertainty associated with an estimate of metal contained in orogenic gold deposits will differ significantly to those which apply to industrial limestone resources. However they are carried out, these inventory-based estimates are generally compiled by national geological surveys. Good examples include national estimates of sand and gravel aggregate resources in the Netherlands based upon a 3D model derived from data from over 300 000 boreholes (van der Meulen et al. 2005); and a 2004 study used a combination of GIS and borehole data, modified by some environmental and economic criteria to estimate the coal resource available in the UK for underground coal gasification (Jones et al. 2004).

Wide variation in mineral policy frameworks and resource reporting standards means that the integration of meaningful quantitative data from different jurisdictions can be very difficult. Research currently underway for the European Commission is examining the issues associated with the harmonisation of mineral resource and reserve data across the EU Member States (European Commission, 2014). Preliminary results suggest that harmonisation of national datasets (where they exist) to produce a quantitative assessment of transnational resources is likely to be very challenging.

2.2.2. Estimates based on probabilistic analysis

In an attempt to reduce the bias and sometimes subjective nature of mineral resource assessment the USGS has pioneered a probabilistic approach for quantifying mineral endowment. This method, based on established mineral deposit models and delineation of prospective geology, estimates that there may be approximately 1.3 times as much copper still to be discovered in porphyry copper deposits in the upper one kilometre of crust of the Andes region as identified to date (Cunningham et al. 2008). Whilst providing a valuable indication of the amount of metal remaining in undiscovered deposits in the uppermost part of the Earth, in terms of the total thickness of the continental crust this is barely scratching the surface. The deepest current mine is approaching four kilometres and, as technology evolves, deeper deposits may become economically viable to develop. One of the key objectives of current European initiatives on raw materials is to better define the potential for indigenous resources at greater depths (European Commission, 2013).

An alternative approach to mineral resource assessment is the tectonic-diffusion method, which estimates the number of mineral deposits of a specific type at all levels in the crust. This computational technique uses age-frequency data of known deposits of a particular type, to model the formation of new deposits and to track their vertical movement in the Earth's crust through time (Kesler & Wilkinson 2008). Applying this approach to porphyry copper deposits, Kesler and Wilkinson (2008) estimate that the amount of copper in deposits above 3.3 km (a suggested limit of mining in the foreseeable future) in the Earth's crust could support global mine production of copper at current rates for more than 5000 years. The tectonic-diffusion method is best suited to deposit types, such as porphyry copper mineralisation, with approximately log normal age-frequency distributions (Kesler & Wilkinson 2008). Kesler & Wilkinson (2013) apply this technique to tin deposits associated with granites in an attempt to evaluate the use of tectonic-diffusion analysis for a deposit class with non-ideal age-frequency distributions. Their modelling estimates that, even if only half of the tin identified above one kilometre in the Earth's crust can be discovered and mined, the amount of recoverable tin far exceeds global reserve estimates by the USGS.

Although these studies demonstrate that more robust, quantitative estimates of global mineral endowment are being developed these are generally restricted to the industrial or precious metals occurring in relatively well-constrained deposit classes, which have been the focus of decades of research and for which voluminous data exist. However, even for these commodities, the resource assessments are restricted by our current understanding of ore deposit formation.

2.2.3. Methods of Undiscovered Resource Assessment – The USGS Approach

There are many different reasons for needing to know the amount of undiscovered mineral resources in a particular region, country, or the entire world (Brisky and Schulz, 2007). Stakeholders include governments, planning councils, regulatory agencies, environmental planners, and industries that produce, transform, or consume mineral resources. Similarly there are many different methods for conducting mineral resource assessments ranging from qualitative order of magnitude estimates based on analogy or extrapolation of existing trends, to quantitative estimates based upon numerous inputs of geological, geochemical, remote sensing, and other sources of relevant data that collectively result in a numerical estimate of numbers of deposits, tons of metal, dollar value of contained metals, or some other measure of net worth (Singer and Menzie, 2010). These results can then be filtered based upon economic or environmental factors to predict how much of an undiscovered resource might be possible to develop (Robinson and Menzie, 2013). Furthermore, either qualitative or quantitative assessments can incorporate non-geologic factors such as ecosystem services, environmental sensitivity, or socioeconomic impact (Haines et al., 2014).

The most widely used method of quantitative mineral resource assessment is that developed and employed by the U.S. Geological Survey (USGS) over several decades (Singer, 1993). This methodology has been described in numerous publications and outlined step by step by Menzie et al. (2005) and Singer (2007). Figure 3 is a flow chart illustrating the overall process.

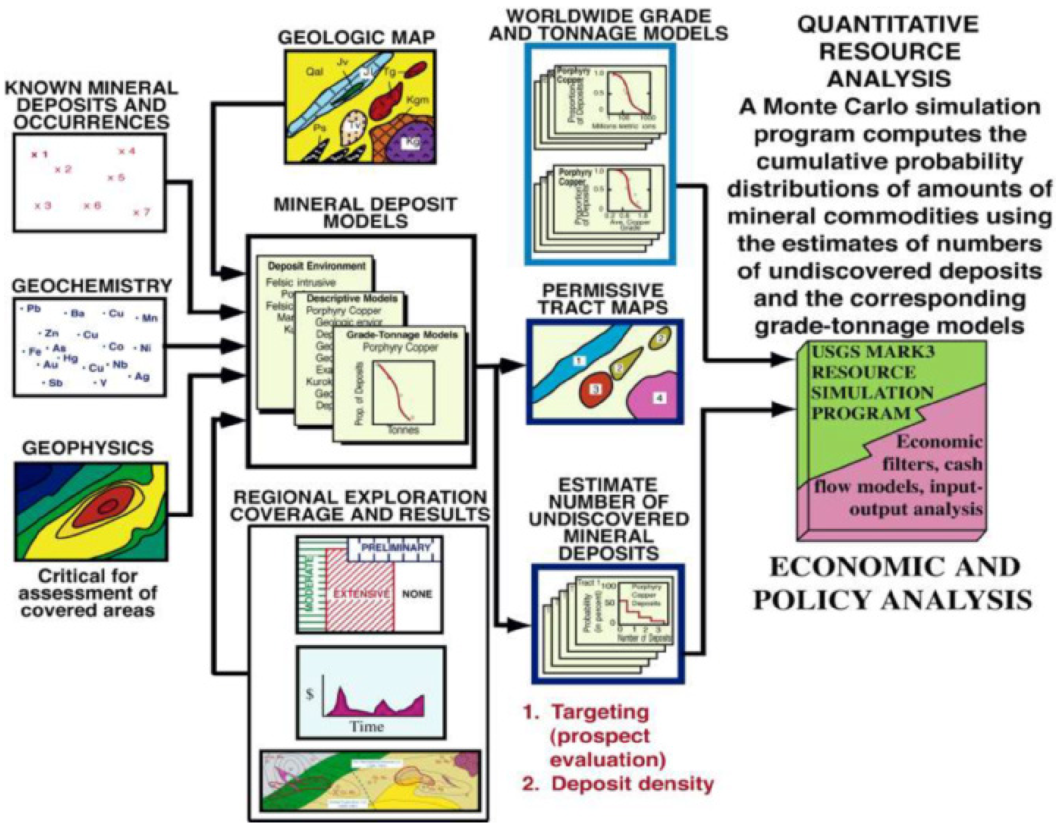


Figure 3: Flow chart illustrating multiple steps of USGS 3-part method for assessing undiscovered mineral resources (from Singer, 2007).

The method addresses two basic questions: (1) where are undiscovered mineral resources likely to exist, and (2) how much undiscovered mineral resource may be present? Geographic areas that may contain undiscovered resources are shown on maps. Quantitative discussions of the amounts of undiscovered resources and qualitative discussions of the likelihood of undiscovered resources both are included in the typical assessment reports. Results of quantitative assessments are presented as ranges of amounts of in-place, undiscovered metal.

The first step of a mineral resource assessment is to gather needed information such as:

- Geologic maps (determines scale of assessment)
- Mineral deposit models (keystone to assessment)
- Mineral occurrence database (need accurate locations)
- Geophysics (subsurface information for tract delineation)

- Geochemistry (surface information for tract delineation)
- Remote sensing (surface information for tract delineation)
- Exploration history (How well has an area been explored?)

The more information that is available the better will be the assessment, but at a minimum it is necessary to have adequate geologic maps and mineral deposit models. The mineral deposit model is the keystone in combining the diverse information related to mineral resources. Descriptive mineral deposit models document the characteristics that guide the delineation of the permissive tract for each type. Models summarize essential attributes of the deposit type and are used to distinguish areas that are permissive for the deposit type from those that are not. Information on the tonnages and grades of well-explored deposits of a given type are used as models for tonnages and grades of undiscovered deposits of the same type in similar geologic settings.

Permissive tracts are delineated by analogy with similar geologic settings containing known deposits elsewhere and boundaries are drawn around areas where geology and other information such as geophysics and known occurrences permit the existence of deposits of one or more specified types and within specified constraints such as depth < 1km below the surface (Fig. 4). Boundaries are drawn such that the probability of deposits outside the boundary is negligible.

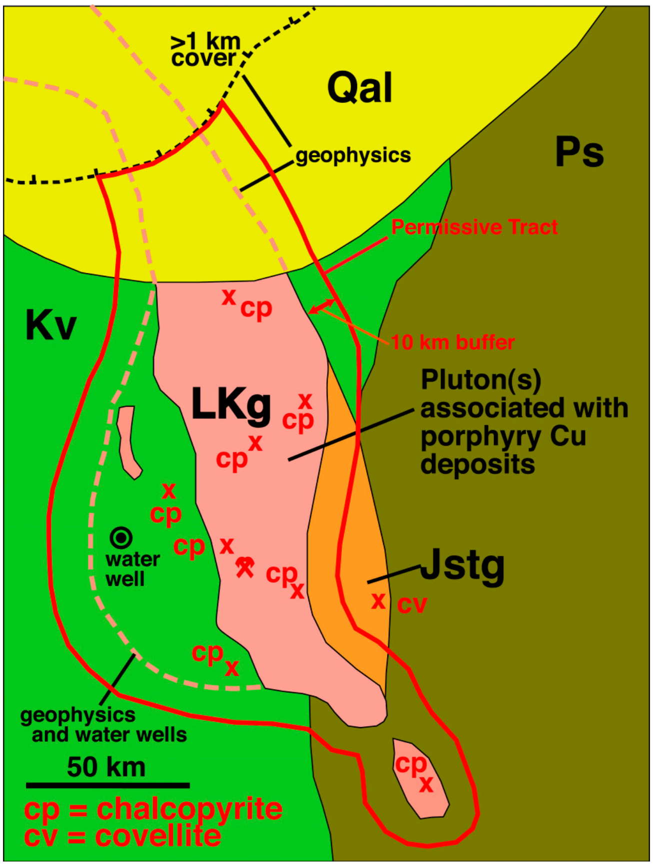


Figure 4: Boundary of permissive tract is drawn based upon known geology and analogy with the appropriate mineral deposit model (from Singer, 2007).

The second step is for a team of experts on the deposit types, region of interest, and assessment methodology to make probabilistic estimates of numbers of undiscovered deposits using some form of analogy that incorporates:

- Deposit density (number of deposits per unit area from well-explored regions)

- Relative frequency of related deposit types (e.g., more polymetallic vein deposits than porphyry Cu deposits)
- "Process constraints"—The more likely the combination of geologic processes required to form a deposit type, the more likely the deposit type should occur
- Exploration history (How well has an area been explored?)

Estimates are made to be consistent with the characteristics of deposits with identified resources as described in the grade and tonnage models. The estimates are made at different confidence levels using a variety of estimation strategies to express the degree of belief that some fixed but unknown number of deposits exists within the permissive tract. These estimates represent a measure of the favourability of the tract and of the estimator's uncertainty about what may exist (Singer and Menzie, 2010).

In the third step these estimates for each permissive tract are combined with grade and tonnage data (Fig. 5) to provide a probabilistic estimate of amounts of resources that could be contained in undiscovered deposits. This is done using Monte Carlo simulation—a computational approach that uses repeated sampling to obtain results. Monte Carlo simulation was done with the program, EMINERS (Duval, 2012); the computational process is described by Root and others (1992). Simulation results are reported at selected percentiles, together with the mean expected amount of metal, the probability of the mean, and the probability of no resources being present. The results are estimates of the minimum amount of metal associated with different probabilities of occurrence (percentiles). The probability distribution gives a range of values that conveys the uncertainty associated with the estimate. For example, there could be a 90-percent chance of a small amount of metal, a 50-percent chance of a moderate amount of metal, and a 10-percent chance of a relatively large amount. These estimates all describe the in-place undiscovered metal resources.

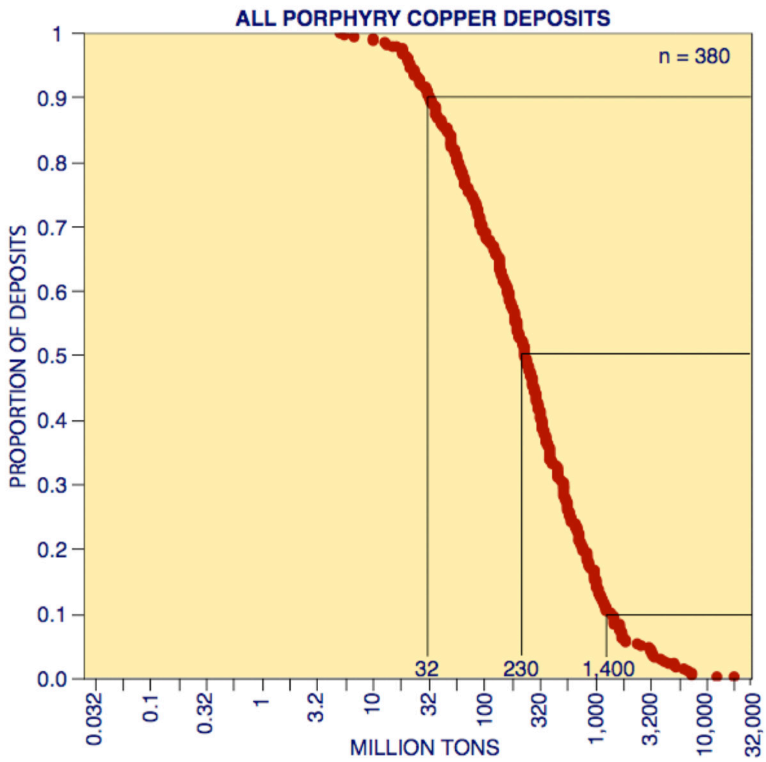


Figure 5: Tonnage distribution of porphyry Cu deposits. Each point represents a deposit and intercepts are at the 90th, 50th, and 10th percentile (from Singer, 2007).

Following the completion of the assessment, results are presented to an internal review committee for evaluation and approval. The committee's comments are addressed prior to finalizing the report for formal technical review and publication. Only then is the completed assessment presented to policymakers, other stakeholders, and the public. The most recent example of the application of the USGS 3-part method is the global copper assessment that yielded an estimate of 3.5 Gt of undiscovered copper among 225 tracts around the world (Johnson et al., 2014). To put this in perspective annual U.S. copper consumption is 2 Mt and global consumption is 20 Mt. The USGS assessed undiscovered copper in two deposit types, porphyry and stratiform Cu, that account for about 80 percent of the world's copper supply. Results of the assessment were published by deposit type for 11 regions (Johnson et al., 2014). Approximately 50 percent of the global total occurs in South America, South Central Asia and Indochina, and North America combined (Fig. 6).

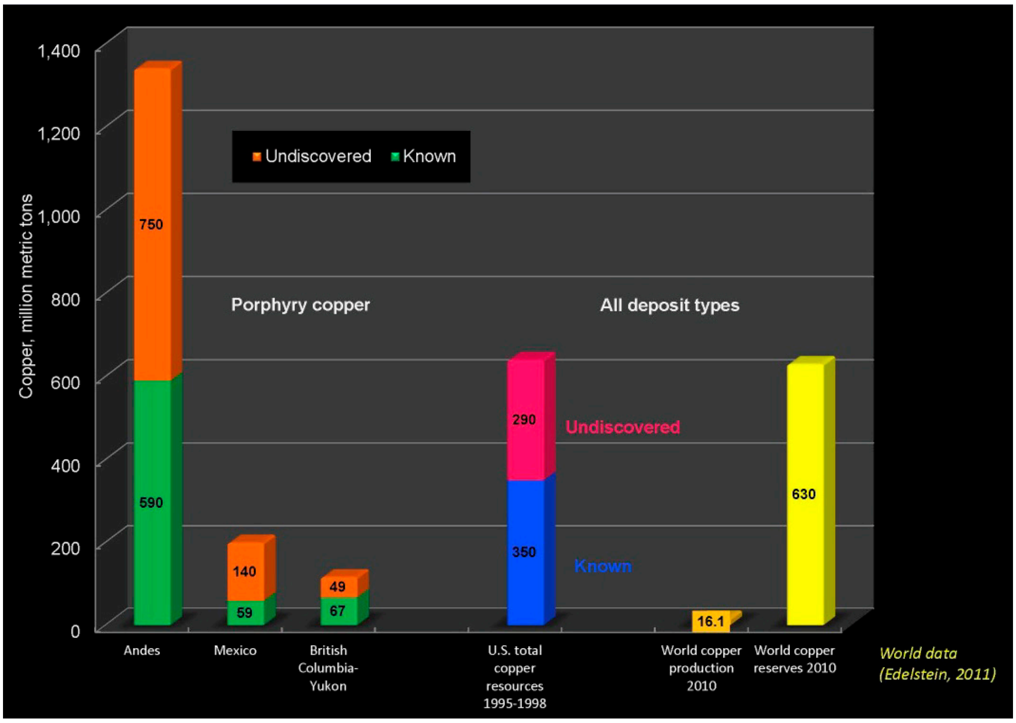


Figure 6: Distribution of known and undiscovered copper in four of eleven assessed regions from the 2013 USGS global Cu assessment compared to 2010 world copper production and reserves (Edelstein, 2011, Johnson et al., 2014).

The USGS 3-part methodology is the best known and most widely accepted form of undiscovered mineral resources assessment. But there are other methodologies that can be used including mineral prospectivity mapping (Carranza and Sadeghi, 2010), one-level prediction (McCammon and Kork, 1992), and tract delineation using fractal (Raines, 2008), weights of evidence (Bonham-Carter et al., 1989), weighted logistic regressions (Raines and Mihalasky, 2002), and data-driven evidential belief functions (Carranza and Hale, 2003). It is beyond the scope of this paper to compare the many possible methods of doing resource assessments. Rather, the goal has been to briefly describe and illustrate the USGS 3-part method for assessing undiscovered mineral resources and the reader is referred to Singer and Menzie (2010) and the other papers cited in this overview for a more detailed and comprehensive presentation.

2.2.4. The importance of geological data and understanding

Both approaches to mineral resource estimation require high-quality geological information and a good understanding of relevant ore deposit types. These factors vary enormously from place to place and commodity to commodity. More often than not, geological datasets are lacking and knowledge of mineral deposit classes is poor. This is particularly the case for the so-called ‘technology’ or ‘critical’ metals where long-term supply security assessments might be called into question because of insufficient geological information (Graedel & Nassar, 2013). Thus, valid methodologies for resource estimation have been developed, but they require a comprehensive geological underpinning to provide meaningful resource estimations at regional, national and international scales.

2.3. RESERVES

The reality is that despite increasing metal production over the past 20 years, reserve levels have increased for the commodities shown in Table 1. Concerns regarding physical exhaustion of metals may be based on an over-simplistic view of the relationship between reserves and consumption (i.e. number of years supply remaining equals reserves divided by annual consumption). Metals of which we know the precise location, tonnage and which we can extract economically with existing technology - known as 'reserves' - are tiny in comparison to the total amount. Consumption and reserves change continually in response to scientific advances and market forces.

Table 1: Comparison of USGS reserves for selected minerals (in thousand metric tonnes) from USGS Mineral Commodity Summaries

	1996	2014
Iron (crude ore)	150,000,000	170,000,000
Copper	310,000	690,000
Phosphate rock	11,000,000	67,000,000
Lithium	2,200	13,000

Whilst Table 1 shows reserve figures rising, severe downgrades in reserves have also occurred historically as shown for UK Coal Production in Figure 7, but the realisation only came after 87% of coal production had occurred.

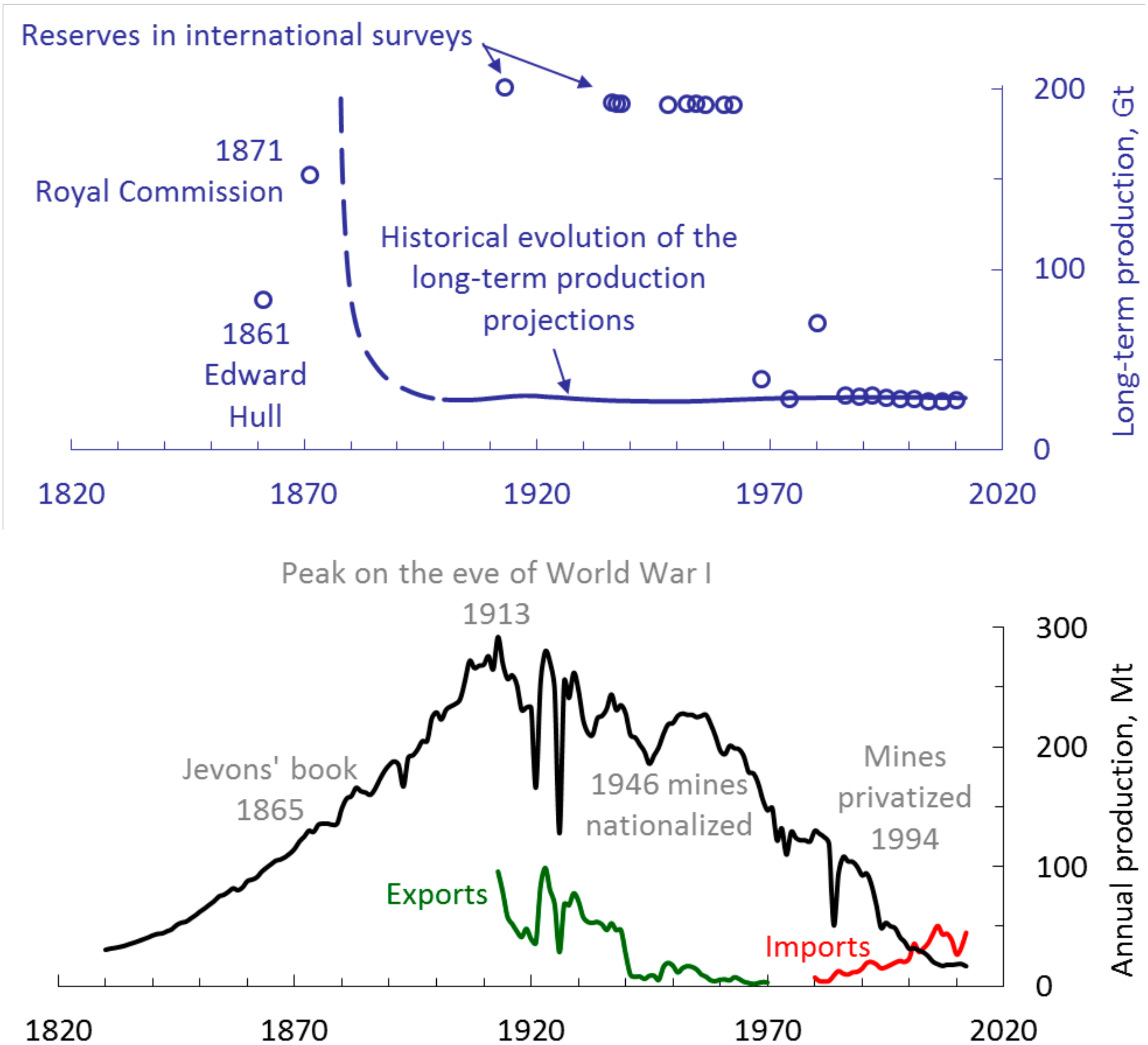


Figure 7: Change in reserve estimates for UK Coal over time (upper figure) overlaid with actual annual UK coal production in the lower figure (Rutledge, 2013).

Thus reserves are best considered as working inventories at a particular point in time, varying in response to the rate of extraction of raw materials, to new discoveries and numerous economic, political, social and environmental factors. In addition, estimates of global mineral reserves are not necessarily reliable. For many commodities uncertainty in these estimates arises from the fact that they are derived from a wide range of disparate sources that do not use a common system for classifying and reporting reserves. Consequently, because of their dynamic nature and the inherent uncertainties in global totals, published reserve estimates should not be regarded as reliable indicators of future availability of mineral commodities (Lusty and Gunn, 2014).

2.4. COMPARISON OF APPROACHES

A comparison of approaches between inventory and probabilistic approaches is shown in Table 2.

Table 2: Comparison of requirements and outputs of the various inventory and probabilistic methods for crustal resource estimation

	Inventory				Probabilistic	
	Based on geological data		**Based on licence data**		**USGS**	**Tectonic diffusion**
	Metallic minerals	**Industrial & construction minerals**	**Metallic minerals**	**Industrial & construction minerals**	**Metallic minerals only**	**Metallic minerals only**
Requirements						
Geological mapping	Essential	Essential	Desirable	Desirable	Essential	Non-essential
Geophysics	Desirable	Non-essential	Non-essential	Non-essential	Essential	Non-essential
Geochemistry	Desirable	Non-essential	Non-essential	Non-essential	Essential	Non-essential
Understanding of age-relationships and tectonic setting	Non-essential	Non-essential	Non-essential	Non-essential	Desirable	Essential
Mineral occurrences	Desirable	Non-essential	Non-essential	Non-essential	Essential	Non-essential
Exploration history	Desirable	Non-essential	Essential	Essential	Essential	Non-essential
Mineral deposit understanding	Desirable	Desirable	Non-essential	Non-essential	Essential	Essential
Grade/ tonnage data	Desirable	Non-essential	Essential	Essential	Essential	Essential
Harmonised reporting standards	Non-essential	Non-essential	Essential	Essential	Non-essential	Non-essential
Data management	Essential	Essential	Essential	Essential	Essential	Essential
Outputs						
Non-geological modification	Yes	Yes	Yes	Yes	Yes	No
Confidence	Low-medium	Medium	Medium-high	Medium-high	Medium	Medium-low
Unknown resources	No	No	No	No	Yes	Yes
Commodity scope	Wide	Wide	Restricted	Restricted	Very restricted	Very restricted
Geographic coverage	Wide	Wide	Restricted	Restricted	Wide	Very wide

Notes:

Requirements

Geological mapping: access to consistent mapping at a regional or national scale;
Geophysics: access to airborne potential field data at a regional or national scale;
Geochemistry: access to consistent regional geochemical data;

Understanding of age-relationships and tectonic setting: age data and tectonic setting of known deposit types of a specific commodity;
Mineral occurrences: spatial information on occurrences of minerals related to specific commodities at a regional or national scale;
Exploration history: information on how well an area has been explored for specific commodities;
Grade / tonnage data: the measured grade of known deposits at known locations and tonnages produced;
Harmonised reporting standards: does the grade and tonnage data collected need to be reported to a recognised national or international code;
Data management: will calculation of a resource estimate require capacity to compile and manage large amounts of data;
Outputs
Non-geological modification: can the resource estimate be modified to take into account environmental and/ or socio-economic factors;
Confidence: relative level of confidence in estimates generated;
Unknown resources: does the estimate include undiscovered resources;
Commodity scope: is the methodology capable of incorporating a wide range of commodities;
Geographic coverage: is the methodology capable of covering a large geographic area.

KEY POINTS: RESOURCES & RESERVES

- This section found two key approaches to estimating resources
  - the *first is based on inventories* which itself can be estimated using either (a) geological data or (b) licence data
  - the *second is based on probabilistic assessments* and is for metallic minerals only
- It further discussed that reserves are best considered as a dynamic working inventory at a particular point in time, varying in response to the rate of extraction of raw materials, to new discoveries and technologies and to socio-political, economic and environmental factors
- Key to both is the availability of geological data and understanding regarding the disposition and character of resoiurces in the ground.

3. MODELLING SUPPLY

MODELLING SUPPLY OUTLINE

This section describes:
- time horizons for approaches to modelling supply of minerals (3.1)
- economic approaches to resource scarcity (3.2)
- physical approaches to modelling supply (3.3)
- the role of new technology on supply (3.4)
- approaches to modelling of secondary stocks and production (3.4)

3.1. APPROACHES TO ECONOMIC SCARCITY OF RESOURCES

Three commonly accepted ways of modelling economic scarcity of resources are: (i) the user cost of a resource (Hotelling model), (ii) real price of resource dependence, and (iii) recourse extraction costs.[1] These measures have historically externalised adverse social or environmental impacts. Given increased environmental and social scrutiny in the mining industry, internalisation of these costs would exacerbate economic scarcity by increasing the user costs, the real price of the resource, and its extraction costs. Scarcity can then act as a constraint on supply.

3.1.1. Hotelling Model

The **Hotelling Model** (Hotelling, 1913) states that there are two opposing opportunity costs determining the speed of extraction of a finite mineral and that the cheapest mineral will be depleted first.

1) Scarcity Rent: This is the cost incurred by the user of extracting a scarce resource and being unable to sell it later. The price of a finite mineral is assumed to increase as it is mined and its scarcity increases. This creates an incentive to extract the mineral more slowly waiting for its price to increase, this is called the *shadow price*, which represents the maximum amount that customers will pay for an extra unit of the mineral, and it is the determining factor of the extraction speed (Smith, 1937)
2) Interest Rate: This is the cost incurred by leaving the mineral in the ground, waiting for its value to increase.

This model is basically asking: How much do I extract now and how much do I store for later? The shadow price provides an indicator of a mineral's scarcity. Once a mineral is too scarce, the price will reach the *choking* point and will suppress demand (Solow, 2009). If the shadow price gets too high, the laws of supply and demand come into play and for a finite resource this means being taken out of the market, or substituted via a backstop technology (Nordhaus et al., 1973) such as renewable energy for coal.

There are three main criticisms of the Hotelling approach; unknown overall mineral stocks, few homogeneous ore bodies, and the fact that the cheapest available resource does not always get depleted first because it is not necessarily discovered first.

[1] This section draws from Peak Minerals in Australia: A Review of Changing Impacts and Benefits (Giurco et al, 2009) and Australian Mineral Economics Monograph 24, (AusIMM, 2006)

3.1.2. Real Price Model

The **Real Price** model is built on the Hotelling model above but operates in reverse (Norgaard, 1990). It has been a frequently used and well regarded approach to assessing economic scarcity (Tilton, 2002). The real price of a mineral is described as what someone is willing to give up in order to obtain the mineral. The shadow price is uncertain as it does not account for new technology and resource exploration. The Real Price model uses economic indicators from empirical market data to determine scarcity.

An issue with this method is that not everyone involved in price setting knows the scarcity of the resource. So this model describes the amount of information which price setters have regarding scarcity rather than the actual scarcity of the mineral.

3.1.3. Extraction Costs

Both of the above models are criticised for assuming that the industry operates under constant costs. The **Extractions costs** model incorporates what is not accounted for in the previous methods, the marginal extraction costs and the fixed costs for the mining operation. The marginal extraction cost is the cost occurred by extracting one unit of a resource. The fixed costs are the costs incurred during the establishment of the mining operation, including exploration and installation of the operational infrastructure.

To better determine the supply of a mineral using economic modelling, environmental and social aspects need to be examined closely in order to get a sense of what the marginal and fixed costs of extraction may be. When determining the marginal and fixed costs, examining production constraints such as decreasing accessibility of minerals, declining ore grades, rising oil prices, greenhouse gas emissions, environmental costs, capital costs, fees, levies, taxes and royalties, output constraints, and exploration costs is essential. There are of course other aspects to investigate; technological change, disruptive events, exchange rate variation, government activities, and market structure can all have an important influence on the supply of a particular resource.

Having considered these economic approaches to modelling mineral scarcity, the next sub-section considers physical approaches to modelling supply.

3.2. PHYSICAL APPROACHES TO MODELLING SUPPLY

This section deals with the modelling of supply from terrestrial mineral resources; space mining is not considered here.

3.2.1. Reserves-to-Production Method

One of the most rudimentary ways to model future production of a resource is to calculate the R/P ratio (or the reserves to current production ratio). Whilst the simplicity of this method allows ready replication by others, it implicitly assumes that future production rate and reserves remain constant until the resources are exhausted (as indicated in Figure 8). This profile is unrealistic and the approach, if used at all, should be used with caution (May et al. 2012).

Figure 8: Assumed production profile in the RP method.

3.2.2. Hubbert-like models:

The Hubbert model assumes annual resource production follows a bell-shaped curve, and cumulative production follows an S-shaped curve. The Gaussian distribution, notably used by Bartlett (2006) and the Maggio and Cacciola curve are two variations to the Hubbert curve that while still a symmetric bell shaped curve are slightly different to the Hubbert curve. There are also two asymmetric variants to the Hubbert curve, namely the Gompertz curve (Höök and Aleklett, 2009; Feng et al., 2008) and the so-called Verhulst curve used by Roper (2014). The various Hubbert like curves are shown in Figure 9 fitted to UK coal production statistics[2].

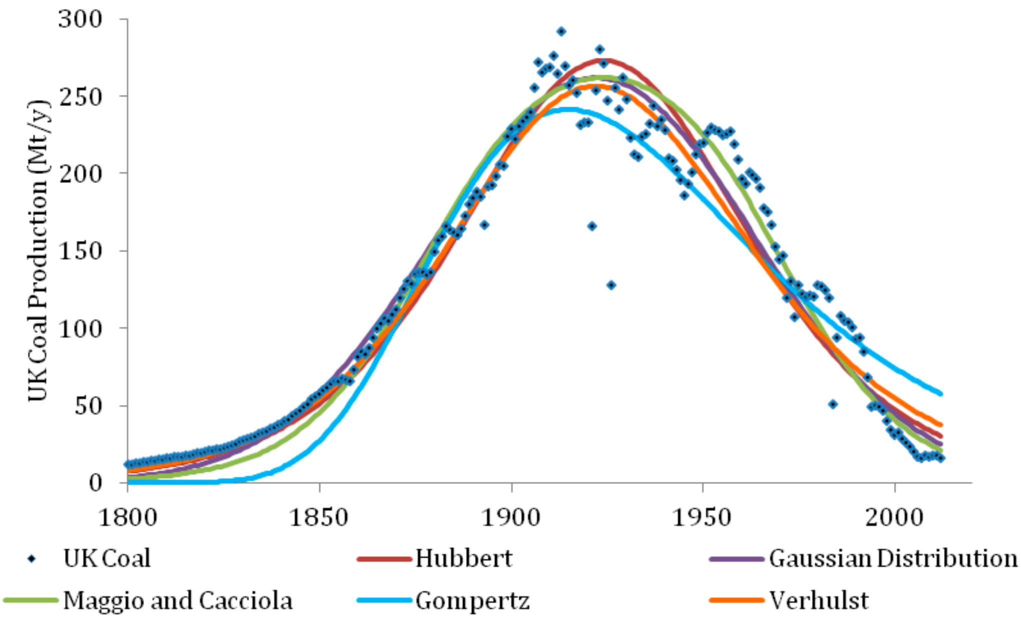


Figure 9: Various models fitted to UK coal production.

The bell shaped curves all model UK coal production with a reasonable accuracy with the exception of the Gompertz curve. While these curves are still readily replicated by others, they are incapable of handling disruptions to supplies due to wars, depressions and so on, which for commodities like gold, make the curve a poor fit.

3.2.3. Modified Hubbert Curves

The main method used to handle historic data which have disruptions to production is by using multi-cycle Hubbert curves (Nashawi 2010). That is fitting an arbitrary number of Hubbert curves, until the model satisfactorily replicates historic production. An alternative method is to use a Generalised Hubbert curve (Mohr and Evans, 2010; Guseo et al., 2007). In this method one single

[2] Updated from Mohr and Evans 2009

Hubbert curve is used, but temporary disruptions to production are handled by inserting anomalies into the function which have an exponential term enabling the effects of the disruption to decay over time. Both the multi-cycle Hubbert curve and the Generalised Hubbert curve approaches can still be replicated by others. However a key disadvantage remains in that production is assumed to be endogenous in the sense that the level of demand does not influence it, rather only the ultimately recoverable resources for potential supply (area under the curve).

3.2.4. Geologic Resource Supply – Demand Model

The Geologic Resource Supply – Demand model (GeRS-DeMo) is an algorithm method that works by determining when idealised mines and fields (for oil and gas) go online. In GeRS-DeMo demand and supply are modelled and influence each other. Whilst supply is limited by the Ultimately Recoverable Resources, demand influences supply in two ways:

1) A high demand increases (or a low demand decreases) the number of new mines or fields scheduled to be brought on-line and
2) It changes the production from the idealised mines and fields (e.g., by temporarily shutting a mine down early and restarting it later).

While the model can no longer be expressed as a function, GeRS-DeMo can still be replicated by others as the model is publicly available (Mohr 2012). While GeRS-DeMo takes into account demand, it does not examine the socio-economic system in which the production occurs. Furthermore, the demand function is currently expressed simply as an intensity of use per person multiplied by population, but could be developed further.

3.3. SYSTEM DYNAMIC MODELS

System dynamic models project minerals production based on parameters such as: production costs, mineral discoveries, tax costs, ore-grade decline, capital and energy requirements and waste flows. Some of these models have been developed by organisations such as: NEMS and WEPS from the EIA (EIA, 2003; EIA, 1997) and WEM (IEA 2008). While others have been developed by small groups of researchers e.g., WOCAP developed by Bakhtiari, (2004), WESM made by Greene et al. (2003) and unnamed models created by de Castro et al. (2009), Cai (2010), and van Vuuren et al. (1999). While these models are able to include influences for the wider system, they can have the issue of being difficult to calibrate, not being publicly available and hence very difficult to reproduce by other researchers. The interaction between environmental and economic factors also has been modelled (O'Regan and Moles, 2006).

3.4. MODEL COMPARISON

The different type of models used to project mineral production each have various advantages and disadvantages as indicated in Table 2.

Table 3: The advantages and disadvantages of different model types for modelling supply

Feature	RP	Hubbert Like Curves	Modified Hubbert Curves	GeRS-DeMo	System Dynamic Models
Readily Applied	Yes	Yes	Yes	Yes	No
Realistic Profile	No	Depends on mineral	Yes	Yes	Yes
Accounts for disruptions	No	No	Yes	Yes	Yes
Accounts for demand	No	No	No	Yes	Yes
Accounts for wider system influences	No	No	No	No	Yes

3.5. A NOTE ON SUPPLY OUTLOOK AND TECHNOLOGY

For oil resources it is common to project future supply decades ahead, considering (i) production from current fields, (ii) discovered but yet-to-be-developed fields and (iii) yet-to-be-discovered resources. However, for minerals such multi-decadal outlooks are not freely available from government or industry bodies, with estimates instead generally spanning 5-10 years and not disaggregated into production from current, yet-to-be-developed and yet-to-be-discovered mines (Giurco et al., 2014).

Whilst commercial intelligence firms model production over longer time horizons, costs for accessing such data are high. In recent decades there has been increasing interest in such modelling by academic researchers, for example using cumulative production trajectories based estimates of ultimately recoverable resources and population-led demand growth (coal (Mohr, 2009; Rutledge, 2011), copper (Northey et al., 2014)). For steel the approaches to forecasting demand range from regression approaches (Crompton, 1999) and intensity-of-use models (Crompton, 2000) to dynamic material flow models in Japan broken down to the level of in-use stocks, obsolete stocks and overall stocks (Daigo et al., 2007) and to end-use sectors and per-capita stock trajectories (Pauliuk et al, 2013).

This White Paper proposes that detailed modelling of supply trajectories is an integral part of assessing commodities of potential concern beyond 2030.

Technological change could have a significant effect on future supply. This applies to both the ability to supply cheap energy to underpin mining of declining ore grades which require more energy and to mining and mineral processing technologies themselves, such as in-situ mining or ocean mining in place of conventional mining.

3.6. RECYCLING AND SECONDARY SOURCES

Recycling metals has a long tradition and three aspects are important – (i) the need to quantify stocks of secondary sources (ii) the rates of production from recycling and (iii) the complexity of processing 'urban ores'.

The focus on comprehensively assessing above-grounds stocks of resources has increased in recent years, in the USA via the Stocks and Flows project at Yale and also at an international level through the work of the International Resource Panel (Graedel et al. 2011). Unlike government-funded geological surveys which provide companies with pre-competitive information on the location of terrestrial resources, equivalents are not common for mapping above ground stocks of resources.

The role of metal supply from secondary sources relative to primary production varies by metal. Whilst global steel scrap use was around 570 million tonnes (World Steel Recycling in Figures 2008-2012), this is approximately only a third of crude steel production. By contrast, Figure 10 shows that for elements like lead, ruthenium and niobium the percentage of secondary scrap in the total input to metal production is above 50%, albeit for much smaller production volumes.

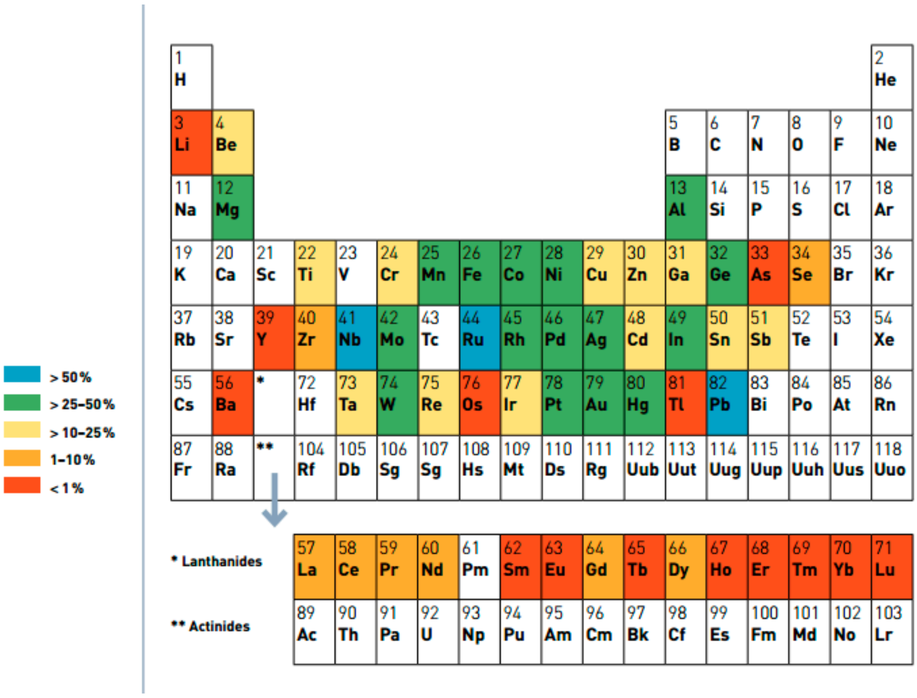


Figure 10: The periodic table of global average recycled content (RC, the fraction of secondary [scrap] metal in the total metal input to metal production] for sixty metals. Uncoloured boxes indicate that no data or estimates were available or that the element was not addressed by the authors of the study (Graedel et al., 2011).

Whilst the US Geological Survey provides current and *historical* data on secondary metal production, publicly available *forecasts* for rates of secondary metal production are more difficult to identify than for primary production (Giurco et al., 2009). The most prominent approach is that of dynamic material flow analyses (for example Zeltner et al., 1999) generally undertaken by research scholars, rather than government agencies. Econometric modelling of secondary markets is less common than for primary production, although Blomberg and Söderholm (2009) developed an econometric model for secondary aluminium.

Finally, the importance of understanding connections between metal cycles when modelling secondary stocks and the distinct geology of urban ores relative to natural ores has been highlighted by Reuter et al. (2013). Whilst a wind mill in the 1700s contained six metals, a wind turbine will now contain 45, which increases the complexity of the recycling task.

MODELLING SUPPLY SUMMARY

This section found:

- *A range of tools are available for looking at supply trajectories under different conditions.*
- *It is challenging to represent within these models the step changes that may occur over time in technology, culture, costs of external factors such as energy, water and labour, environmental concern and attitudes to consumption and recycling.*
  - *All of these introduce added uncertainty into the modelled outcome and so the calculations should be considered conceptual and conservative.*

4. COMMODITY SUPPLY CASE STUDIES

CASE STUDIES OUTLINE

This section describes for selected commodities the current state of knowledge regarding resource supply and the timeframes on which security of supply becomes challenged. This point is termed "peak mineral".

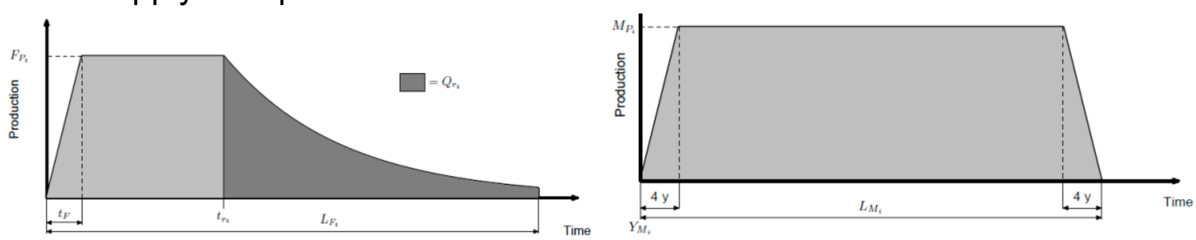
4.1. INTRODUCTION AND MODEL DESCRIPTION

This section presents the projections of world production of a variety of minerals. These projections have been created using GeRS-DeMo. GeRS-DeMo was initially created to project fossil fuel production for the world (Mohr 2010). The first section in the report explains the definitions of a variety of terms used. The next section, illustrates how GeRS-DeMo works. Following this, the projections of 6 key minerals (coal, iron ore, copper, phosphate, lithium and helium) are presented as well as a summary table showing the estimated peak year. Next, the commodity specific results are presented for each of the 6 commodities.

The University of Technology, Sydney has developed a Geologic Resource Supply-Demand Model (GeRS-DeMo) capable of projecting the production of a geologic resource. The model has been explained in full in Mohr (2010), and less extensively elsewhere (Mohr and Evans, 2013; Mohr et al., 2012, Mohr and Ward (2014), and Northey et al., 2014). The model has a supply (from either mines or oil/gas fields) and a demand component. The scenario can either be dynamic, where the supply and demand components interact, or static, where they do not interact.

The Ultimately Recoverable Resources (URR) is defined as the total amount of the resource that can be recovered before production starts. Specifically, to be counted as part of the URR the resource only to be (or assumed to be) economically and technologically recoverable at some point in time. It is possible that some of the URR is left unexploited, if for instance, climate change policies result in limitations to fossil fuel extraction. Furthermore, the resource does not need to be economically or technically recoverable currently.

4.1.1. Supply Component



A) Idealised field (for Helium from Natural Gas) B) Idealised mine (other commodities)

Figure 11: The idealised field and mine profiles.

The supply component has two production types, fields (for oil and gas production) and mines. The supply for both production types works by placing idealised field and mines online that are assumed to have a production profile as shown in Figure 11. The total supply for a given region is determined by the sum of the production of all idealised mines or fields. The model determines the number and size of mines or fields to place online in each year. In the dynamic version, the percentage difference between supply and demand influences the number of mines or fields brought online. If demand is sufficiently high (and the model is operating in dynamic mode) a mine can upgrade to where the plateau production level is doubled. Similarly if demand is sufficiently low, mines and fields already in production can be shut down, and restarted at a later date.

Supply – Fields

The production of individual idealised fields as shown in Figure 11 has a one year ramp up to a plateau period, followed by an exponential decline in production. The profile shown can be expressed in terms of the URR of the field (Ultimately Recoverable Resource). There remain two things to calculate, first, the number of fields on-line over time, and second the URR of the individual fields. The number of fields on-line, $n(t)$ is determined by:

$$n(t) = \left\lceil r_F n_T \frac{Q(t)}{Q_T} \right\rceil$$

where n_T is the total number of fields to be placed on-line, r_F is a rate constant, Q_T is the URR of the region, and $Q(t)$ is the cumulative production. The calculation of the URR of the individual field, is determined via the calculation of the exploitable URR. The exploitable URR, is the sum of the URR in fields that have already been brought on-line. The exploitable URR $Q_e(t)$ is estimated from:

$$Q_e(t) = Q_T \left(\frac{n(t)}{n_T} \right)^{r_Q}$$

where r_Q is a rate constant. The URR of an individual field brought on-line in year t, $Q_F(t)$ is determined from:

$$Q_F(t) = \frac{Q_e(t) - Q_e(t-1)}{n(t) - n(t-1)}$$

Supply – Mines

As shown in Figure 11 the idealised mine has a four year ramp up and ramp down period, with a steady production rate in between. The life of an individual mine and its production rate is dependent on the year the mine is brought on-line as described in the following equations:

$$L_M(t) = \frac{L_H + L_L}{2} + \frac{L_H - L_L}{2} \tanh\left(r_t (t - t_t)\right)$$

$$M_P(t) = \frac{M_H + M_L}{2} + \frac{M_H - M_L}{2} \tanh\left(r_t (t - t_t)\right)$$

where r_t and t_t are rate and time constants, M_L, M_H is the minimum and maximum mine production rates, and L_L, L_H are the minimum and maximum mine lives. The method for determining the rate and time constants is described in Mohr (2010). It remains to calculate the number of mines brought on-line in year t. This is achieved via calculating an estimated exploitable URR $Q_E(t)$ as:

$$Q_E(t) = \frac{Q_T - Q_{T1} \exp(-r_T)}{1 - \exp(-r_T)} - \frac{Q_T - Q_{T1}}{1 - \exp(-r_T)} \exp\left(-r_T \frac{Q(t)}{Q_T} \right)$$

where Q_{T1} is the URR of the first mine brought on-line in the region and r_T is a rate constant. The number of mines brought on-line is determined by increasing the number of mines on-line until the actual exploitable URR is larger than the estimated exploitable URR.

4.1.2. Demand

The demand (when used in the modelling to upgrade supply from mines where demand exceeds supply) is calculated by multiplying the population by the per-capita demand. The global population *p(t)* (in billions) is assumed to stabilise at around 10 billion (UN 2008) based on the following equation (shown in Figure 12):

$$p(t) = \frac{10 - 0.82}{\left[1 + 1.5\exp\left(-0.046(t - 2007)\right)\right]^{1/2}} + 0.82$$

The per-capita demand, *D(t)* is calculated as:

$$D(t) = \begin{cases} D_M \exp\left(r_d(t - t_d)\right) & ; t < t_d \\ D_M & ; t \geq t_d \end{cases}$$

Where D_M is the maximum per-capita demand, r_d is a rate constant and t_d is the year per capita reaches D_M.

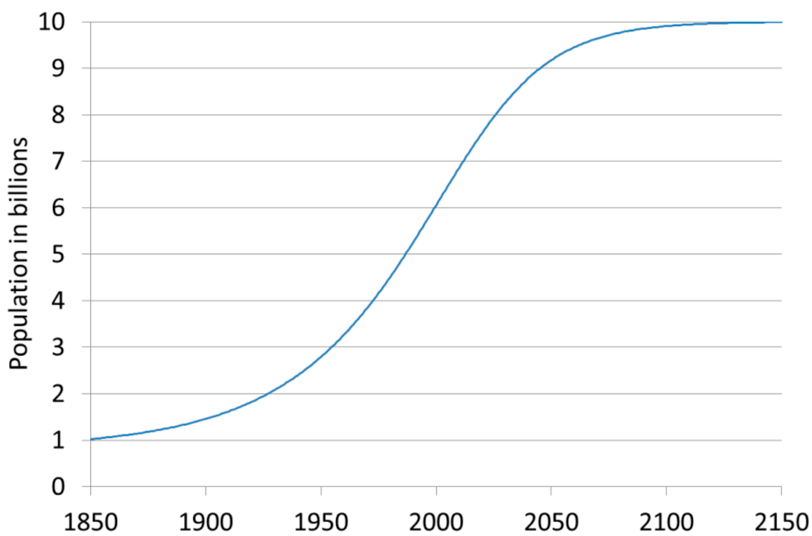


Figure 12: The projected world population.

4.2. MODEL RESULTS – SUMMARY

Summary data for the projected supply modelling for coal, iron ore, copper, lithium and helium are shown in Table 4 and Figure 13.

Table 4: URR numbers used in the supply projections

Resource	URR	Peak Year	Peak rate	Units	Max per capita demand	Reference
Coal	22406	2020	245.8	EJ	60 GJ/person	Mohr et al., 2014a
Iron ore	346.3	2041	4.69	Gt iron ore	N/A	Mohr et al. 2014b
Copper	2097	2030	25.3	Mt Cu	∞*	Northey et al. 2014
Lithium	23558	2061	285.6	kt Li	N/A	Mohr et al. 2012
Phosphorus	4181	2026	48.6	Mt P	3.5 kg P/person	Mohr and Evans 2013
Helium	9064	2092	90.5	kt He	N/A	Mohr and Ward 2014

* copper per capita demand historically has grown exponentially and this assumes that future demand is greater than supply. A maximum of approximately 10 kg/capita in countries with a GDP/capita of $35,000 and over has been reported (Brewster, 2009)
N/A means no demand was calculated and implies that demand is greater than supply.

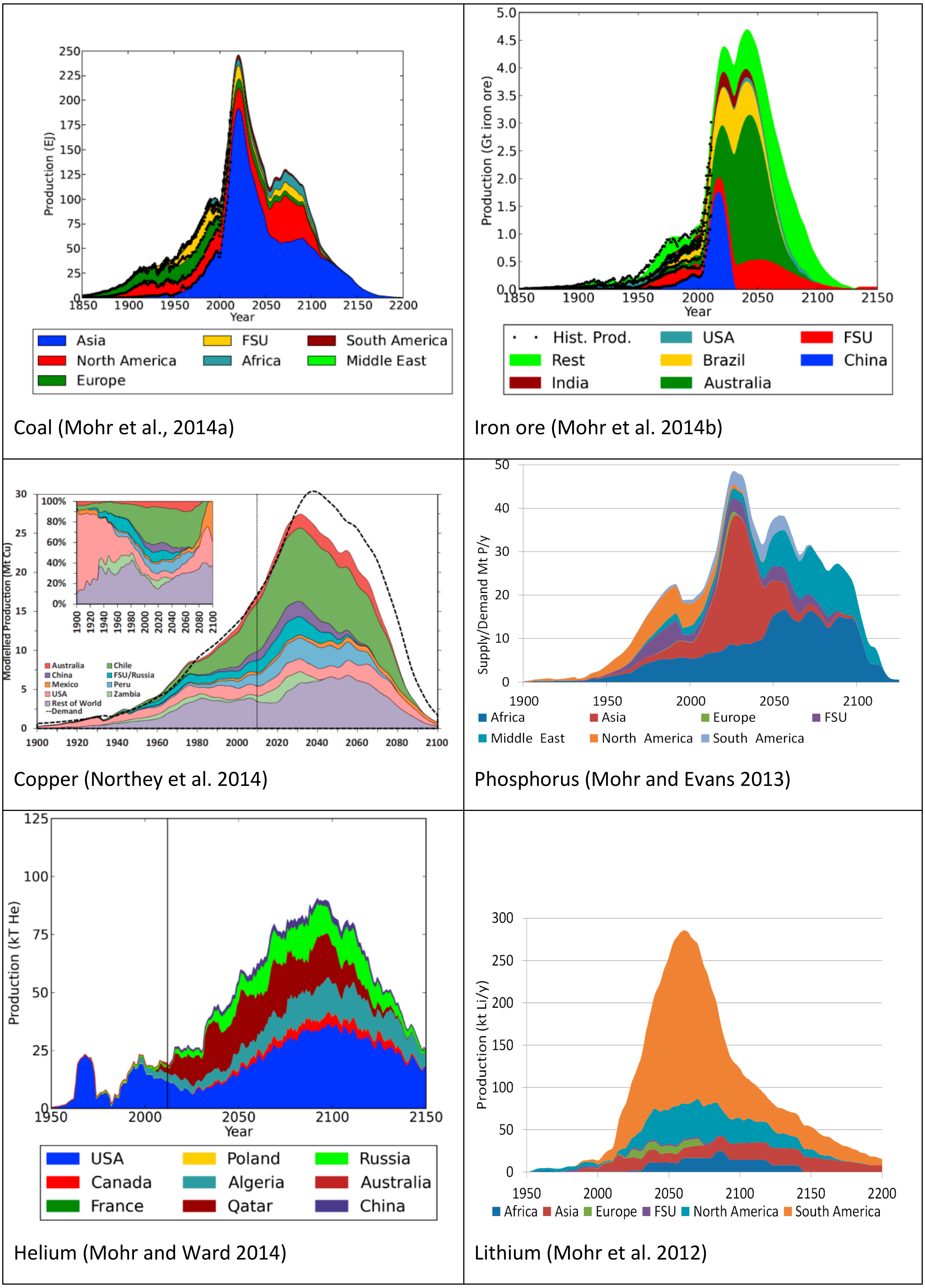


Figure 13: Projections of various minerals production created by GeRS-DeMo.

4.3. MODEL RESULTS – COAL, IRON ORE, COPPER, LITHIUM, PHOSPHOROUS, HELIUM

4.3.1. Coal (Mohr et al. 2014a)

The uses for coal are primarily for electricity generation and in the production of steel. The rapid development occurring in China has corresponded with a rapid increase in Chinese coal production. Specifically, between 2000 and 2012 Chinese coal increased from 1 to 4 Gt/y, by comparison it took the rest of the world approximately 100 years to increase from 1 to 4 Gt/y (see Figure 14). With the rapid growth, China now produces ~50% of the world's coal. While China provides 50% of production and is rapidly increasing production, it only has 22% of the URR.

The URR estimate has been estimated by WEC (2013) resource with cumulative production and Hubbert linearization technique to obtain a total of 22,406 EJ (1161 Gt). As shown in Figure 14 six countries dominate the world URR; these are China, Australia, USA, India, the Former Soviet Union (FSU) and South Africa.

Due to the dominance of Chinese coal production, when Chinese coal production peaks in 2020, the world's coal production peaks. This is despite strong growth in the rest of the world's production particularly from Australia, India and USA, even after Chinese production peaks.

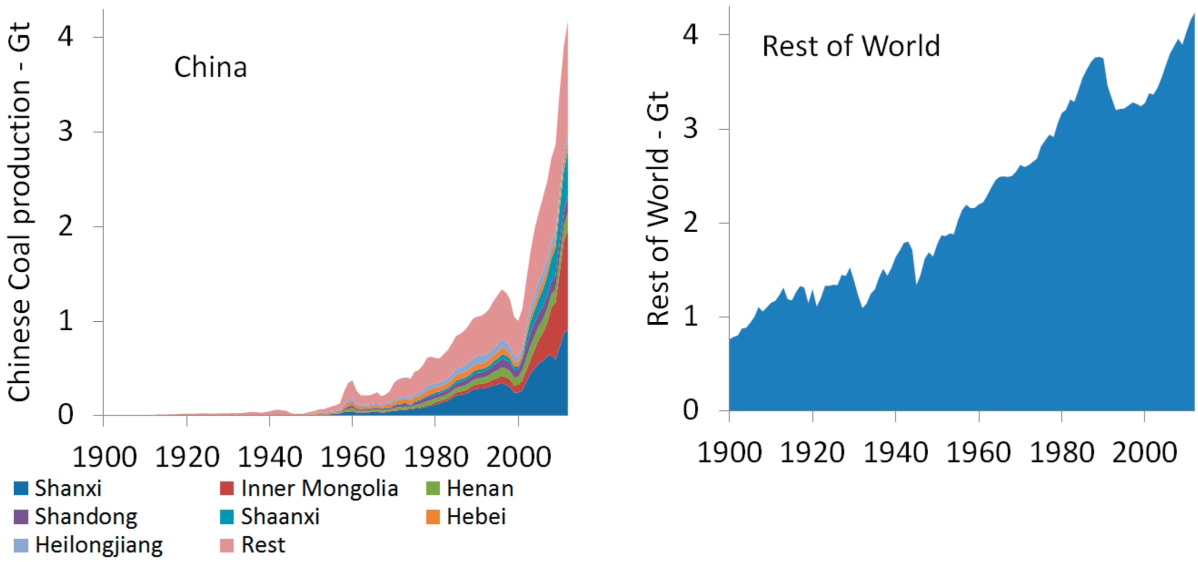


Figure 14: Historic production of Chinese and Rest of World coal production.

Table 5: Coal URR estimate split by country

Country	URR (EJ)	Country	URR (EJ)
China	4 958	Hungary	32
Australia	4 567	Romania	26
USA	4 191	South Korea	22
India	1 703	Netherlands	15
FSU	1 669	Venezuela	14
South Africa	955	New Zealand	14
Indonesia	752	Argentina	14
Germany	746	Zimbabwe	8
UK	661	Bangladesh	7
Poland	338	Philippines	7
Yugoslavia	253	Thailand	7
Columbia	192	Mozambique	5
Czech Rep.	190	Laos	5
North Korea	147	Tanzania	5
Canada	146	Chile	4
Brazil	118	Taiwan	4
Turkey	111	Botswana	4
France	107	Swaziland	4
Japan	71	Austria	4
Belgium	67	Italy	3
Greece	48	Zaire	2
Mongolia	45	Iran	2
Mexico	38	Pakistan	2
Vietnam	38	Niger	2
Bulgaria	37	Other	14
Spain	33	World	22 406

4.3.2. Iron ore (Mohr et al. 2014b)

Iron ore is primarily used in the production of steel that is used throughout our society for cars, bridges and buildings. In a similar trend with coal, the booming Chinese economy has resulted in a rapid expansion of Chinese iron ore production from 224 Mt/y in 2000 to 1330 Gt/y in 2011. This growth corresponds to an increase in world's share of production from 20% to 44%. Once again, although China dominates production, it only has 10% of the URR (as shown in Table 6).

The URR estimate in Table 5 was calculated by adding resource estimates to cumulative production wherever a resource estimate could be found. For countries where a resource estimate could not be sourced, USGS (various years) reserves plus cumulative production were used.

Although Chinese iron ore production does peak in the near future (2017) world production peaks after 2040, due to rapidly growing production in Brazil and Australia offsetting Chinese declines.

Table 6: Iron ore URR by country

Country	URR (Gt iron ore)	Country	URR (Gt iron ore)
Australia	109.0	Vietnam	1.0
FSU	45.4	Peru	0.6
Brazil	36.4	Mongolia	0.6
China	34.9	Spain	0.6
USA	14.5	Austria	0.6
India	10.8	Korea	0.6
Cameroon	10.5	Luxemburg	0.5
Nigeria	10.0	Philippines	0.3
Guinea	8.9	Turkey	0.3
Canada	8.4	Yugoslavia	0.2
Congo	5.9	Malaysia	0.2
Sweden	5.3	Norway	0.2
South Africa	5.1	New Zealand	0.1
Venezuela	5.0	Czechoslovakia	0.1
Mauritania	4.6	Egypt	0.1
Other Africa	4.3	Romania	0.1
France	3.0	Hungary	0.1
Iran	2.9	Japan	0.1
Sierra Leone	2.7	Bulgaria	0.1
Algeria	2.7	Poland	0.1
Liberia	2.7	Italy	0.1
UK	1.6	Angola	0.1
Chile	1.3	Swaziland	0.1
Senegal	1.2	Tunisia	0.1
Germany	1.1	Other	0.4
Mexico	1.1	World	346.3

4.3.3. Copper (Northey et al 2014)

Copper is used primarily for electrical wiring and pipes. The copper resources for the world were estimated by collating resources from mining and exploration companies. This was converted to a URR by using a recovery rate of 85% based on Gordon (2002) and adding cumulative production. The URR is summarised in Table 6, as shown, the worlds' URR is dominated by Chile which has a third of the URR. With the current URR estimate the peak date in copper production is anticipated to be around 2030. If the URR were increased by 50% it would only push the peak year out by 1 decade to shortly after 2040.

Table 7: URR estimates for copper by country

Country	URR (Mt Cu)	Country	URR (Mt Cu)
Chile	684.3	Poland	41.7
USA	253.5	PNG	29.9
Peru	165.1	Philippines	28.5
FSU	133.4	Argentina	26.8
Australia	130.0	Pakistan	20.6
Canada	86.9	South Africa	19.0
China	86.8	Botswana	17.8
Zambia	75.0	Panama	16.5
Zaire	66.4	Brazil	15.8
Mexico	58.9	India	11.5
Indonesia	58.7	Iran	10.7
Mongolia	46.2	World	2 096.7

The production trajectory can also be illustrated by ore type as shown in Figure 15 which is dominated by porphyry deposits.

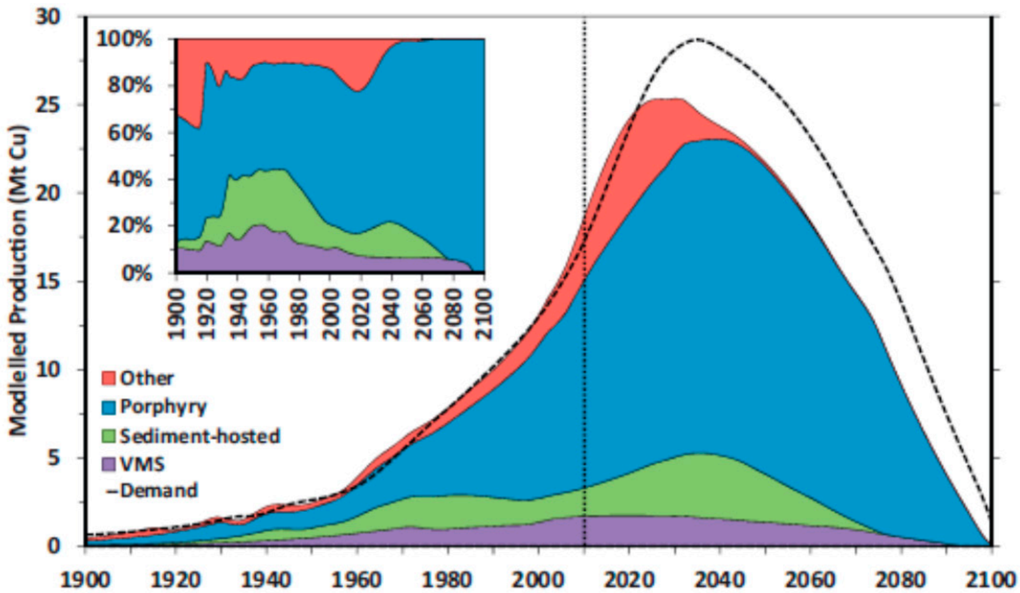


Figure 15: Projection of future copper production by ore type (Northey et al. 2014).

4.3.4. Phosphorus (Mohr and Evans 2013)

Phosphorus is primarily used for fertilisers necessary for food production. The phosphorus URR is a contentious issue, with the main question being: How much does Morocco/Western Sahara have? Recently the International Fertilizer Development Centre (IFDC) (Kauwenbergh et al., 2010) significantly revised upwards the amount of resources Morocco/Western Sahara has to 290 Gt of phosphate rock. Rosemarin et al. (2010) and GPRI (2010) dispute the reliability of this increase. Other than Morocco/Western Sahara, China has considerable resources of phosphate rock, with the remaining resources spread throughout North Africa/Middle East, FSU and USA. As with coal and iron ore, phosphorus production in China is rapidly increasing with China now producing 36% of the world's phosphorus in 2010 compared to just 14% in 2000.

World phosphorus production is anticipated to peak in 2026 due to Chinese production peaking. Future production of phosphorus is difficult to predict given both the uncertainty in the Moroccan URR number, and political issues resulting from the bulk of the phosphorus resource existing within Western Sahara which is territory occupied by Morocco. The current model shows growth in Morocco/Western Sahara increasing at a very slow rate. Ultimately, the uncertainty surrounding both stability to mine the phosphorus deposit and the size of the resources in Morocco/Western Sahara, means that the future production of phosphorus is difficult to predict.

Table 8: Phosphorus URR by country

Country	URR (Mt P)	Country	URR (Mt P)
Morocco/Western Sahara	1 000	Brazil	69
China	774	Senegal	35
USA	362	Syria	27
FSU	357	Togo	24
Iraq	234	Christmas Island	22
Jordan	211	Finland	21
Egypt	177	Nauru	14
Saudi Arabia	157	Mexico	13
Peru	118	India	12
Australia	110	Guinea Bissau	9
Vietnam	88	New Zealand	6
South Africa	83	Korea	5
Tunisia	81	Burkina Faso	4
Israel	74	Other	21
Algeria	72	World	4 181

4.3.5. Lithium (Mohr et al 2012)

Currently around 50% of lithium is used for batteries and as an additive to glass. With the rising prominence of lithium ion batteries, it is likely that lithium ion batteries will dominate the demand for lithium in the future. Lithium extraction is a rarity in that it is extracted in to very distinct formats, the first is by mineral ore (typically spodumene) and second by extracting lithium salts from brine sources such as lakes and salars. Historically production was dominated by ore deposits, but since 1990 most lithium is sourced from brines sources in South America, notably Chile and Argentina.

The URR for lithium is shown in Table 8. As shown, brine sources dominate the URR with Chile, Boliva, USA, China and Argentina, with some ore resources in Australia, Canada and USA. The URR estimate was determined by a detailed literature search for each deposit.

The inputs to projection for lithium assumed that there will be strong demand for lithium ion based batteries for electric vehicles. The lithium projection is anticipated to peak shortly after 2060.

Table 9: Lithium URR by country and basin

Country	Basin	URR (kt Li)	Country	Basin	URR (kt Li)
Chile	Atacama	7 605	Zaire	Manono	1 501
Chile	Maricunga	220	Canada	Fox Creek	258
Chile	*Total*	*7 825*	Canada	La Corne	163
Bolivia	Uyuni	3 560	Canada	Separation Rapids	56
USA	North Carolina	1 000	Canada	Wekusko	54
USA	hectorite	1 000	Canada	Bernic Lake	33
USA	Smackover	500	Canada	La Motte	23
USA	Salton Sea	316	Canada	Old mines	6
USA	Great Salt Lake	260	*Canada*	*Total*	*592*
USA	North Carolina developed	230	Serbia	Jardarite	425
USA	Historic	165	Australia	Greenbushes	279
USA	Clayton	20	Australia	Mt Cattlin	56
USA	*Total*	*3 491*	Australia	Mt Marion	30
China	All	2 966	Australia	Other	0
Argentina	Rincon	1 400	Australia	Total	364
Argentina	Cauchari	463	FSU	All	180
Argentina	Hombre Muerto	416	Brazil	All	89
Argentina	Olaroz	140	Zimbabwe	Bikita	70
Argentina	Mineral	0	Others		77
Argentina	*Total*	*2 419*	World		23 558

4.3.6. Helium (Mohr and Ward 2014)

Currently 20% of helium is used in MRI scanners, and helium is also used for welding, controlled atmospheres, as a lifting gas, and for applications needing a very cold temperature. Helium historically has been all but completely controlled by USA. Prior to 1974 virtually all helium came from USA, between 1974 and 1996 rest of the world production averaged 11%, and between 1996 and 2012 rest of the world production rapidly increased to 36% of total production due predominantly to Algeria, Qatar, Russia and Australia. The growth in rest of world production has offset declines in USA production between 1997 and 2012.

The URR estimate has been calculated using USGS (various years) reserve plus cumulative production for rest of the world, and the URR for USA was determined by Pacheco and Ali (2008). Helium production is shown to be able to have strong growth in production for the rest of the century with a peak projected at the end of the 2100.

Table 10: Helium URR by country

Country	URR (kt He)
USA	4 178
Qatar	1 723
Algeria	1 435
Russia	1 177
Canada	340
China	186
Poland	15
Australia	8
World	9 064

4.4. DISCUSSION

GeRS-DeMo has been used to create projections of future production for six commodities, namely coal, iron ore, copper, phosphorus, lithium and helium. Each has had production modelled on a country-by-country basis. The commodities have a wide variety of production profiles from a sharp peak (coal) to smooth bell curves (copper) to undulating production (phosphorus). The peak year estimates of these minerals range considerably from 2020 (coal) to towards the end of the century (helium).

The development of such models adds an important set of baseline data to discussions regarding the adequacy of supply, which will also depend on factors affecting future demand (which have not been explored in this paper) and on the economic, social and environmental impacts of production.

KEY FINDINGS

This section found that:

- *the peak year for the more common bulk commodities studied (phosphorus, iron ore, copper, coal) is expected to occur before 2050 and within the next thirty years.*
- *however, this is based on certain assumptions regarding resource potential in differing countries which could be inherently conservative.*

5. CONCLUDING DISCUSSION

With the suggestion that peak minerals for some of our most common commodities could occur within the next three decades, the imperative to increase our knowledge of the global resource base is clear. This requires concerted effort in geoscientific investigation around the globe.

An uncertain future could radically alter assumptions about productivity, technology, population, social and environmental concerns and costs, the technological ability to recycle and the appetite for greater resource productivity through re-use.

Factors which will influence the future include:

- **Land access** – decreasing due to population/urban growth, geopolitical instability, social licence pressures from communities, resource lock up in parks and preserves; versus increases from new frontiers – ocean, seafloor, extra-terrestrial
- **Geologic knowledge** – mapping, geochemistry, geophysics
- **Energy and water** – cheap and widely distributed versus expensive and localized
- **Technology** – game changers for exploration (laser drilling/analysis, drones with high res lidar, spectral) and extraction (in situ mining and metallurgy by solution or robotics)

How do we handle these dynamic factors in predictions of global supply and demand to assess whether we have enough resource to support our future generations?

Securing the future supply of raw materials, energy and water is essential to underpin present prosperity and to aid the development of emerging economies (Lambert, 2001). Along with climate change it is one of the big challenges facing humankind over the next 20 years and more. Geoscientists have a role to play in both in the discovery and environmentally responsible extraction of those materials. However, they cannot work alone and to obtain the social licence necessary to pursue those activities, they must work with other scientific disciplines, including the social sciences.

This White Paper has been written to encourage debate within the geoscientific community and involving industry, academe and national geological surveys. A prime purpose is to assess whether there is an appetite to work together, to identify what are the immediate and longer term scientific and technological challenges, to assess if there is any willingness to share data, to identify research and other work priorities and to define what role, if any, IUGS has in that, possibly as an honest broker. Does the Resourcing Future Generations, as presently envisaged, adequately address "the problem," and, indeed, is there a problem of a magnitude that needs the implied new approach?

We invite your thoughts, contributions and criticisms. Please send them to rfg@geolsoc.uk

REFERENCES

Ayres, R. U., Ayres, L., and Råde, I. (2011). The life cycle of copper, its co-products and by-products.

Bakhtiari, A. M. S. (2004). World oil production capacity model suggests output peak by 2006-07. Oil and Gas Journal, 102(16):18–20.

Bartlett, A. A. (2006). A depletion protocol for non-renewable natural resources: Australia as an example. Natural Resources Research, 15(3):151–164.

Bonham-Carter, G. F., Agterberg, F. P., and Wright, D. F., (1989). Weights of evidence modelling: a new approach to mapping mineral potential: In: Agterberg, F. P., Bonham-Carter, G. F. (Eds.), Statistical Approach in the Earth Sciences: Geological Survey of Canada, Paper, 89-9, p. 171–183.

Brewster, N. (2009). Outlook for commodity markets, Rio Tinto Economics. MF Global Seminar 15 October 2009.

Briskey, J. A., and Schulz, K. J., eds. (2007). Proceedings for a Workshop on Deposit Modeling, Mineral Resource Assessment, and Their Role in Sustainable Development: U.S. Geological Survey Circular 1294, 143 p.

Bloodworth, A., Gunn, G., and Lusty, P. (2010). Malthus Revisited? *Earthwise 26* British Geological Survey.

Cai, Z.; Clarke, R. H., Glowacki, B. A., Nuttall, W. J., and Ward, N. (2010). Ongoing ascent ot the helium production plateau – Insights from system dynamics. Resources Policy, 35, 77–89.

Carranza, E. J. M, and Sadeghi, M. (2010). Predictive mapping of prospectivity and quantitative estimation of undiscovered VMS deposits in Skellefte district (Sweden): Ore Geology Reviews, v. 38, p. 219-241.

Carranza, E. J. M, and Hale, M. (2003). Evidential belief functions for geologically constrained mapping of gold potential, Baguio district, Philippines: Ore Geology Reviews, v. 22, p. 117–132.

Crompton, P. (1999). Forecasting steel consumption in South–East Asia. Resources Policy, 25(2), 111–123.

Crompton, P. (2000). Future trends in Japanese steel consumption. Resources Policy, 26(2), 103–114.

Cunningham, C. G., Zappettini, E. O., Waldo and Vivallo, S., et al. (2008). Quantitative Mineral Resource Assessment of Copper, Molybdenum, Gold, and Silver in Undiscovered Porphyry Copper Deposits in the Andes Mountains of South America. USGS Open-File report 2008–1253.

Daigo, I., Igarashi, Y., Matsuno, Y., and Adachi, Y. (2007). Accounting for steel stock in Japan. ISIJ international, 47(7), 1065–1069.

Duval, J. S. (2012). Version 3.0 of EMINERS—Economic Mineral Resource Simulator: U.S. Geological Survey Open-File Report 2004–1344, http://pubs.usgs.gov/of/2004/1344J.

Edelstein, D. L. (2013). Copper, *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2011, v. 1, p. 20.1–20.25, accessed January 24, 2014 at http://minerals.usgs.gov/ minerals/pubs/commodity/copper/myb1-2011-coppe.pdf.

European Commission. (2013). Strategic Implementation Plan for the European Innovation Partnership on Raw Materials Part II Priority Areas, Action Areas and Actions.

European Commission. (2014). Minventory project website. http://www.minventory.eu/index.html

Geoscience Australia. (2014). Australia's Identified Mineral Resources 2013. Geoscience Australia, Canberra.

Giurco, D., McLellan, B., Franks, D., Nansai, K., and Prior, T. (2014). Responsible mineral and energy futures: views at the nexus, Journal of Cleaner Production (in press) DOI: 10.1016/j.jclepro.2014.05.102

Gordon R. B. (2002). Production residues in copper technological cycles. Resources, Conservation and Recycling 36:87–106.

GPRI. (2010). GPRI Statement on Global Phosphorus Scarcity, September 26, 2010.

Graedel, T. E. et al. (2011). Assessing Mineral Resources in Society: Metal Stocks & Recycling Rates. UNEP.

Graedel, T. E., and Nassar, T. (2013). The Criticality of Metals: A Perspective for Geologists. In: Jenkin, G. R. T., Lusty, P. A. J., McDonald, I., Smith M. P., Boyce, A. J., & Wilkinson, J. J. (eds) Ore Deposits in an Evolving Earth. Geological Society, London, Special Publications, 393. First published online October 10, 2013, doi 10.1144/SP393.6

Haines, S. S., Diffendorfer, J. E., Balistrieri, L., Berger, B., Cook, T., DeAngelis, D., ... and Walton-Day, K. (2014). A framework for quantitative assessment of impacts related to energy and mineral resource development. Natural Resources Research, 23(1), 3–17

Hotelling, H. (1913). The economics of exhaustible resources. The Journal of Political Economy., 39.

Johnson, K. M., Hammarstrom, J. M., Zientek, M. L., and Dicken, C. L. (2014). Estimate of undiscovered copper resources of the world, 2013: U.S. Geological Survey Fact Sheet 2014–3004, 3 p., *http://dx.doi.org/10.3133/fs20143004*.

Jones N. S, Holloway S, Creedy D. P, Garner K, Smith N. J. P, Browne, M. A. E. and Durucan, S. (2004). UK Coal Resource for New Exploitation Technologies. Final Report. *British Geological Survey* Commissioned Report CR/04/015N.

Kesler, S. E. and Wilkinson, B. H. (2008). Earth’s copper resources estimated from tectonic diffusion of porphyry copper deposits. Geology, 36, 255–258.

Kesler, S. E. and Wilkinson, B. H. (2013). Tectonic-Diffusion Estimates of Global Mineral Resources: Extending the Method – Granitic Tin Deposits. In: Jenkin, G. R. T., Lusty, P. A. J., McDonald, I., Smith M. P., Boyce, A. J., and Wilkinson, J. J. (eds) Ore Deposits in an Evolving Earth. Geological Society, London, Special Publications, 393. First published online October 7, 2013, doi 10.1144/SP393.6

Lambert, I., Durrheim, R., Godoy, M., Kota, M., Leahy, P., Ludden, J., Nickless, E, Oberhaensi, R, Anjian, W., and Williams, N. (2013). Resourcing Future Generations: A proposed new IUGS initiative.

Lambert, I. B. (2001). Mining and sustainable development: considerations for minerals supply. In Natural resources forum (Vol. 25, No. 4, pp. 275–284). Blackwell Publishing Ltd.

Lusty, P. A. J. and Gunn, A. G. (2014). Challenges to global mineral resource security and options for future supply. In: Jenkin, G. R. T., Lusty, P. A. J., McDonald, I., Smith M. P., Boyce, A. J., and Wilkinson, J. J. (eds) Ore Deposits in an Evolving Earth. Geological Society, London, Special Publications, 393. First published online October 10, 2013, doi 10.1144/SP393.13

Mason, L., Mikhailovich, N. Mudd, G. Sharpe, S. and Giurco, D. (2013). Advantage Australia: resource governance and innovation for the Asian century, prepared for CSIRO Minerals Down Under Flagship by the Institute for Sustainable Futures (UTS, Sydney, Australia) and Monash University, Melbourne.

May, D., Prior, T., Cordell, D., and Giurco, D. (2012). Peak minerals: theoretical foundations and practical application. Natural Resources Research, 21(1), 43–60.

McCammon, R. B., and Kork, J. O. (1992). One-level prediction — a numerical method for estimating undiscovered metal endowment: Nonrenewable Resources, v. 1, p. 139–147.

Menzie, David, Foose, Michael, Schulz, Klaus, and Lampietti, Francois. (2005). A shortcourse on methodologies for the assessment of undiscovered mineral resources: U.S. Geological Survey Open-File Report 2005–1146 (published as a CD-ROM).

Mohr, S. and Ward, J. (2014). Helium production and possible projections, Minerals 4 (1) 130–144.

Mohr, S. H. and Evans, G. M. (2013). Projections of future phosphorus production, Philica (380).

Mohr, S. H., and Evans, G. M. (2009). Forecasting coal production until 2100. Fuel, 88(11), 2059–2067.

Mohr, S. H., Jianliang, W., Ellem, G., Ward, J., and Giurco, D. (2014a). Projection of World fossil fuels by country, submitted to Fuel.

Mohr, S. H., Mudd, G. M. and Giurco, D. (2012). Lithium resources, production: critical assessment and global projections, Minerals 2 (1) 65–84.

Mohr, S. (2010). Projection of world fossil fuel production with supply and demand interactions, Ph.D. thesis, University of Newcastle, Australia, http://www.theoildrum.com/node/6782.

Mohr, S., Giurco, D., Yellishetty, M., Ward, J., and Mudd, G. (2014b). Projection of iron ore production, submitted to Natural Resources Research.

Mudd, G. M. (2014). The future of yellowcake: a global assessment of uranium resources and mining: Science of the Total Environment, v. 472, p. 590–607.

Mudd, G. M., and Jowitt, S. M. (2014). A Detailed Assessment of Global Nickel Resource Trends and Endowments. Econ Geol In Press.

Mudd, G. M., Weng, Z., Jowitt, S. M., Turnbull, I. D., and Graedel, T. E. (2013a). Quantifying the recoverable resources of by-product metals: The case of cobalt: Ore Geology Reviews, v. 55, p. 87–98.

Mudd, G. M., Weng, Z. and Jowitt, S. M. (2013b). A detailed assessment of global Cu reserve and resource trends and worldwide Cu endowments. Economic Geology, v. 108, p. 1163–1183.

Norgaard, R. B. (1990). Economic Indicators of Resource Scarcity: A Critical Essay. *Journal of Environmental Economics and Management,* 19, 19–25.

Northey, S., Mohr, S., Mudd, G. M., Weng, Z., and Giurco, D. (2014). Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resources, Conservation and Recycling, 83, 190–201.

O'Regan, B., and Moles, R. (2006). Using system dynamics to model the interaction between environmental and economic factors in the mining industry. Journal of cleaner production, 14(8), 689–707.

Pacheco, N., Ali, S. F. Helium Resources of the United States. (2007). Technical Report. Note 429, U.S. Department of the Interior, Bureau of Land Management, 2008.

Pauliuk, S., Milford, R. L., Müller, D. B., and Allwood, J. M. (2013). The steel scrap age. Environmental science & technology, 47(7), 3448–3454.

Porwal, A. K., and Kreuzer, O. P. (2010). Introduction to the Special Issue: Mineral prospectivity analysis and quantitative resource estimation: Ore Geology Reviews, v. 38, p. 121–127.

Raines, G. L. (2008). Are fractal dimensions of the spatial distribution of mineral deposits meaningful?: Natural Resources Research, v. 17, p.87–97.

Raines, G. L., and Mihalasky, M. J. (2002). A reconnaissance method for delineation of tracts for regional-scale mineral-resource assessment based on geologic-map data: Natural Resources Research, v. 11, p. 241–248.

Reuter, M. A., Hudson, C., Van Schaik, A., Heiskanen, K., Meskers, C., and Hageliken, C. (2013). Metal Recycling: Opportunities, Limits, Infrastructure, a Report of the Working Group on Global Metals Flows to the International Resource Panel. International Resources Panel: Paris, France.

Robinson, G. R., Jr., and Menzie, W. D. 2012, revised 2013. Economic filters for evaluating porphyry copper deposit resource assessments using grade-tonnage deposit models, with examples from the U.S. Geological Survey global mineral resource assessment: U.S. Geological Survey Scientific Investigations Report 2010–5090–H, v. 1.1, 21 p. and data tables, available at http://pubs.usgs.gov/sir/2010/5090/h/.

Root, D. H., Menzie, W. D., and Scott, W. A. (1992). Computer Monte Carlo simulation in quantitative resource estimation: Natural Resources Research, v. 1, no. 2, p. 125–138.

Rosemarin, A., Schröder, J., Dagerskog, L., Cordell, D., and Smit, B. (2010). Future supply of phosphorus in agriculture and the need to maximise efficiency of use and reuse, International Fertiliser Society, Conference paper 10th December 2010, Proceedings 685.

Rutledge, D. (2013). Projections for Ultimate Coal Production from Production Histories Through 2012, 2013 GSA Annual Meeting, Denver, Colorado.

Singer, D. A. (1993). Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, p. 69–81.

Singer, D. A. (1995). World class base and precious metal deposits—A quantitative analysis: Economic Geology, v. 90, p. 88–104.

Singer, Donald A. (2007). Short course introduction to quantitative mineral resource assessments: U.S. Geological Survey Open-File Report 2007–1434 [http://pubs.usgs.gov/of/2007/1434/].

Singer, D. A., and Menzie, W. D. (2010). Quantitative mineral resource assessments—An integrated approach: New York, Oxford University Press, 219 p.

Smith, A. (1937). *An Inquiry into the Nature and Causes of the Wealth of Nations,(1776)*, Methuen.

Solow, R. M. (2009). The economics of resources or the resources of economics. *Journal of Natural Resources Policy Research,* 1, 69–82-69–82.

The Economist. (2013). Towards the end of poverty. Available online http://www.economist.com/news/leaders/21578665-nearly-1-billion-people-have-been-taken-out-extreme-poverty-20-years-world-should-aim Accessed October 2014.

United Nations. (2013). World Population Prospects: The 2012 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.227.

United States Geological Survey. Mineral Commodity Summaries. Technical report, United States Geological Survey. Various years http://minerals.usgs.gov/minerals/pubs/mcs/

Van der Meulen, M. J., van gessel, S. F. and Veldkamp, J. G. 2005. Aggregate resources in the Netherlands. *Netherlands Journal of Geosciences — Geologie en Mijnbouw*, 84–4, 379–387.

Van Vuuren, D. P., Strengers, B. J., and De Vries, H. J. (1999). Long-term perspectives on world metal use—a system-dynamics model. Resources Policy, 25(4), 239–255.

WEC 2013. World Energy Council, Survey of energy resources.

Weng, Z., Mudd, G. M., Jowitt, S. M., and Haque, N. (2015). A Detailed Assessment of Global Rare Earth Element Resources: Opportunities and Challenges, Econ Geol In Press.

Zeltner, C., Bader, H. P., Scheidegger, R., and Baccini, P. (1999). Sustainable metal management exemplified by copper in the USA. Regional Environmental Change, 1(1), 31–46.