British Geological Survey

Risk list 2015 — Current supply risk for chemical elements or element groups which are of economic value.

Element or element group	Symbol	Relative supply risk index	Leading producer	Top reserve holder
rare earth elements	REE	9.5	China	China
antimony	Sb	9.0	China	China
bismuth	Bi	8.8	China	China
germanium	Ge	8.6	China	
vanadium	V	8.6	China	China
gallium	Ga	8.6	China	
strontium	Sr	8.3	China	China
tungsten	W	8.1	China	China
molybdenum	Mo	8.1	China	China
cobalt	Co	8.1	DRC	DRC
indium	In	8.1	China	
arsenic	As	7.9	China	
magnesium	Mg	7.6	China	Russia
platinum group elements	PGE	7.6	South Africa	South Africa
lithium	Li	7.6	Australia	Chile
barium	Ba	7.6	China	China
carbon (graphite)	C	7.4	China	China
beryllium	Be	7.1	USA	
silver	Ag	7.1	Mexico	Peru
cadmium	Cd	7.1	China	
tantalum	Ta	7.1	Rwanda	Australia
rhenium	Re	7.1	Chile	Chile
selenium	Se	6.9	Japan	China
mercury	Hg	6.9	China	
fluorine	F	6.9	China	South Africa
niobium	Nb	6.7	Brazil	Brazil
zirconium	Zr	6.4	Australia	Australia
chromium	Cr	6.2	South Africa	Kazakhstan
tin	Sn	6.0	China	China
manganese	Mn	5.7	China	South Africa
nickel	Ni	5.7	Indonesia	Australia
thorium	Th	5.7		USA
uranium	U	5.5	Kazakhstan	Australia
lead	Pb	5.5	China	Australia
iron	Fe	5.2	China	Australia
carbon (diamond)	C	5.2	Russia	Australia
titanium	Ti	4.8	Canada	China
copper	Cu	4.8	Chile	Chile
zinc	Zn	4.8	China	Australia
aluminium	Al	4.8	Australia	Guinea
gold	Au	4.5	China	Australia

Supply risk index runs from 1 (green — very low risk) to 10 (red — very high risk)

Limitations and methodology are set out in accompanying notes

British Geological Survey

Risk List 2015

An update to the supply risk index for elements or element groups that are of economic value

The updated risk list provides a simple indication of the relative risk in 2015 to the supply of 41 elements or element groups that we need to maintain our economy and lifestyle. This is an update of a similar assessment carried out in 2011 and 2012. The position of an element on this list is determined by a number of factors that might affect availability. These include the location of current production and reserves, and the political stability of those locations. ***New for 2015 companion metal fraction production (i.e. the percentage of a metal that is mined as a by-product) has been incorporated into the analysis, whilst scarcity (previously based on crustal abundance figures) has been removed.*** Data sources used in the compilation of the list are internationally recognised and publicly available.

The risk list highlights a group of elements for which global production is concentrated in very few countries. The restricted reserve distribution and the relatively low political stability ratings for some major producing countries combine to significantly increase risk to supply. This is compounded by low rates of recycling and limited substitutes for many of these elements. Concern about rare earth element supply has received significant attention over the last five years and this element group remains at the top of the list. However, the list highlights other economically important metals with similar high levels of risk to supply disruption including antimony (with application as a fire retardant), bismuth (used in numerous medical applications), platinum group metals (active components in auto-catalysts), and tungsten (a key hard metal used in most cutting tools). ***These elements, particularly the rare earth elements and antimony, have low recycling rates and a limited number of substitutes. They are also almost exclusively mined as by-product metals.*** The list also shows the continued dominance of China in production of many metals and minerals. China is now the leading global producer of 23 of the 41 elements and element groups on the list (Figure 1).

The risk list provides an indication of which elements might be subject to supply disruption, most likely resulting from non-geological factors such as geopolitics (e.g. 'haves' seeking to influence 'have nots') or resource nationalism (e.g. state intervention in production and trade), along with other factors such as labour strikes, accidents and infrastructure availability. Policy-makers, industry and consumers should be concerned about supply risk and the need to ensure diversified supply of primary resources. Equally important will be the need to make full use of secondary resources and recycling, and to reduce our intensity of resource use i.e. 'do more with less'.

With the exception of substitutability the list focuses on risks to supply and does not include any assessment of factors that influence demand, such as criticality of an element to a particular technology.

An in-depth discussion of the risk list methodology and limitations can be found below.

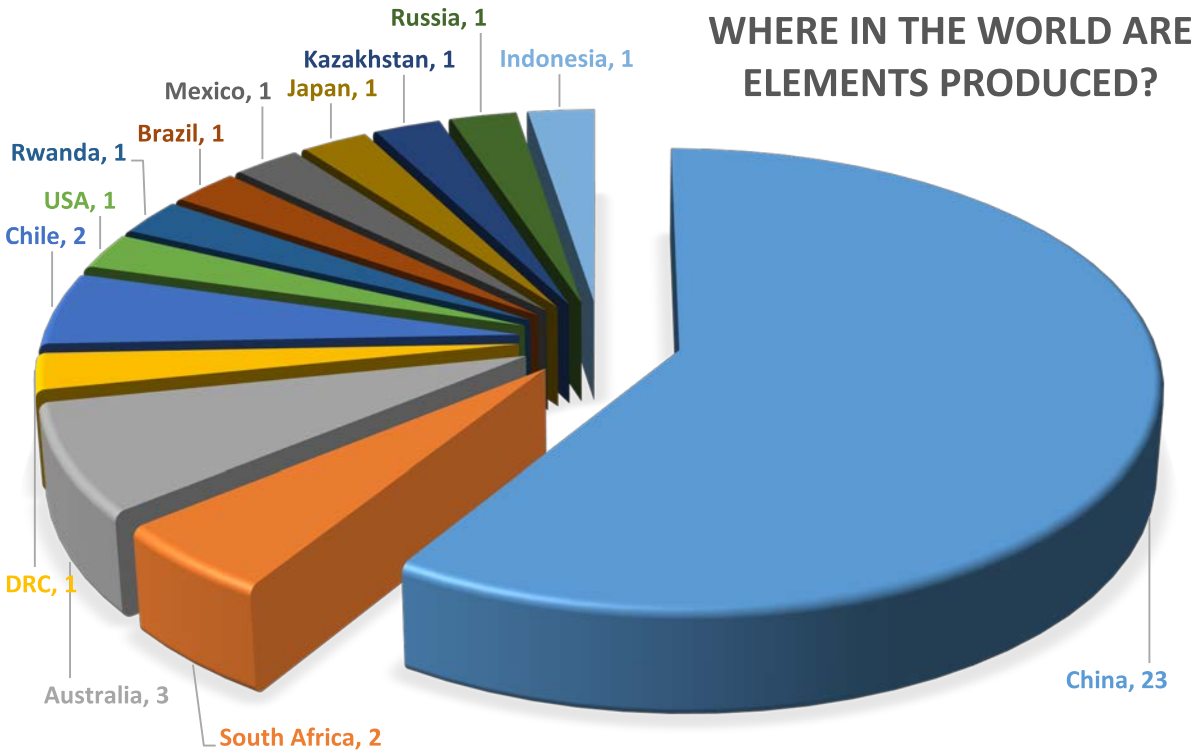

Figure 1. The chart shows the number of times a country is the leading global producer of an element or element group of economic value. ***Source: BGS World Mineral Statisitics***

Methodology for estimating the relative risk to supply of the chemical elements

The following methodology was used to define the relative risk to supply of the following elements:

Silver (Ag); Aluminium (Al); Arsenic (As); Gold (Au); Barium (Ba); Beryllium (Be); Bismuth (Bi); Diamond; Graphite; Cadmium (Cd); Cobalt (Co); Chromium (Cr); Copper (Cu); Fluorspar; Iron (Fe); Gallium (Ga); Germanium (Ge); Mercury (Hg); Indium (In); Lithium (Li); Magnesium (Mg); Manganese (Mn); Molybdenum (Mo); Niobium (Nb); Nickel (Ni); Lead (Pb); Platinum Group Elements (PGE - Ruthenium (Ru), Palladium (Pd), Osmium (Os), Iridium (Ir) and Platinum (Pt)) ; Rhenium (Re); Rare Earth Elements (REE - Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb) and Lutetium (Lu)); Antimony (Sb); Selenium (Se); Tin (Sn); Strontium (Sr); Tantalum (Ta); Thorium (Th); Titanium (Ti); Uranium (U); Vanadium (V); Tungsten (W); Zinc (Zn); and Zirconium (Zr).

Elements not included are those for which insufficient data exist.

An Excel spreadsheet was used to rank the above elements in terms of the relative risk to supply. The ranking system was based on seven criteria scored between one and three.

1. Production concentration
2. Reserve distribution
3. Recycling Rate
4. Substitutability
5. Governance (top producing nation)
6. Governance (top reserve-hosting nation)
7. Companion metal fraction

A score of one indicates that a particular criterion has a low contribution to supply risk, while a score of three indicates a high risk. The scores for each criterion were summed to determine an overall risk to supply, the larger the score the greater the potential risk to supply. Each criterion was given equal weight. The elements were ranked according to their score and a gradational colour scale applied such that increased risk is indicated by hotter colours.

Production concentration

Where the production of a given commodity is concentrated in a few countries this can increase the risk to supply. For example, about 96 per cent of the world's REE are currently sourced from China. The BGS' World Mineral Production data (2009 – 2013) were used to identify the top three producing countries and the percentage of world supply for which the leading country is responsible.

The percentage production for the top three countries was scored as follows:

1 (low) = <33.3 %
2 (medium) = >33.3 to 66.6 %
3 (high) = >66.6 %

Reserve distribution

Minerals deposits are unequally distributed globally and concentration of reserves in a few countries poses an increased risk to short-term supply. For example, about 95 per cent of the world's reserves of niobium are found in Brazil. We have used mineral reserve data from the USGS to provide an indication of the potential for short-term supply disruption. *Mineral Reserves* are effectively 'working inventories' that are continually revised and updated in light of numerous factors pertaining to mining, metallurgy, economics, marketing, law, and the environment (USGS, 2010). USGS' Commodity Summaries (2014 – 2015) reserves data were used to identify the three countries contributing the largest share to global reserves and the percentage of the world reserves held by the principal country.

The percentage of the global reserves held by the top three countries was scored as follows:

1 (low) = <33.3 %
2 (medium) = >33.3 to 66.6 %
3 (high) = >66.6 %

Where USGS data are unavailable an arbitrary score of 1.5 was allocated. Beryllium, arsenic, cadmium, mercury, germanium, indium, and gallium are allocated a score of 1.5 since reserve information is unavailable. USGS reserve data are also unavailable for uranium. However, reserve data for 2013, available from the World Nuclear Authority (WNA), are used in this analysis.

Recycling rate (recyclability)

Recycling of a commodity contributes to and diversifies supply, thus reducing risk. A higher recycling rate might, for example, lead to a reduction in demand for primary resources. Currently, about 50 per cent of the world's iron is recycled, whilst the recycling rate of beryllium is less than one per cent. The United Nations Environment Programme (UNEP) report on 'Recycling Rates of Metals' (2011) was used to identify the recycling rates of 42 commodities.

The recycling rate was scored as follows:

1 (high) = >30 %
2 (medium) = >10 to 30 %
3 (low) = <10 %

Where data are unavailable an arbitrary score of 1.5 was allocated. Fluorspar, diamond, graphite, uranium, and thorium are allocated a score of 1.5 since recycling rate information is unavailable.

Substitutability

The substitutability (the potential for one commodity to take the place of another in a given application) of a given commodity may reduce risk to supply. The availability of suitable substitutes for a commodity may, for example, lead to a reduction in demand for primary resources of that commodity. Currently substitutes for the rare earth elements are very limited. However, several substitutes exist for copper, including silver, aluminium, fibre optics, steel, and even plastics for some applications. The University of Augsburg report on ‘Materials Critical to the Energy Industry’ (2011)[1] and the updated European Commission (EC) Raw Materials Initiative report ‘Critical Raw Materials for the EU’ (2010)[2] were used to identify the substitutability of 31 commodities.

1 = Low[1] *or* <0.3[2]
2 = Medium[1] *or* 0.3 to 0.7[2]
3 = High[1] *or* >0.7[2]

Where data are unavailable an arbitrary score of 1.5 was allocated. Arsenic, gold, bismuth, diamond, mercury, lead, selenium, tin, strontium, thorium and zirconium are allocated a score of 1.5 since substitutability information is unavailable.

Governance indicators

The political stability of a producing country, or country in which large reserves are held, may impact upon the supply of mineral commodities. For example, supplies may be interrupted by war, government intervention, famine or other forms of unrest. A political stability score was derived from World Bank (WB) governance indicators (2010), for both the leading producing country, and for the country with the largest reserves. The World Bank website provides percentile rank information for 213 countries based on six criteria: voice and accountability; political stability; government effectiveness; regulatory equality; rule of law; and control of corruption. Only political stability was considered as part of this study.

Countries with a political stability percentile of <33.3 per cent were scored 3, those with a percentile between >33.3 and 66.6 per cent were scored 2 and those with a percentile of >66.6 per cent were scored 1.

For each commodity an individual political stability score for both the leading global producer and for the chief reserve holder were scored as follows:

1 (high) = >66.6 %
2 (medium) = >33.3 to 66.6 %
3 (low) = <33.3 %

For example, China (with a WB percentile rank of 27.0) is the leading producing country for rare earth elements, and also has the largest share of global reserves, resulting in a score of three in both cases, while Brazil (with a WB percentile rank of 37.0) is the leading producing country of niobium, and also has the largest share of global reserves, giving it a score of two in both cases.

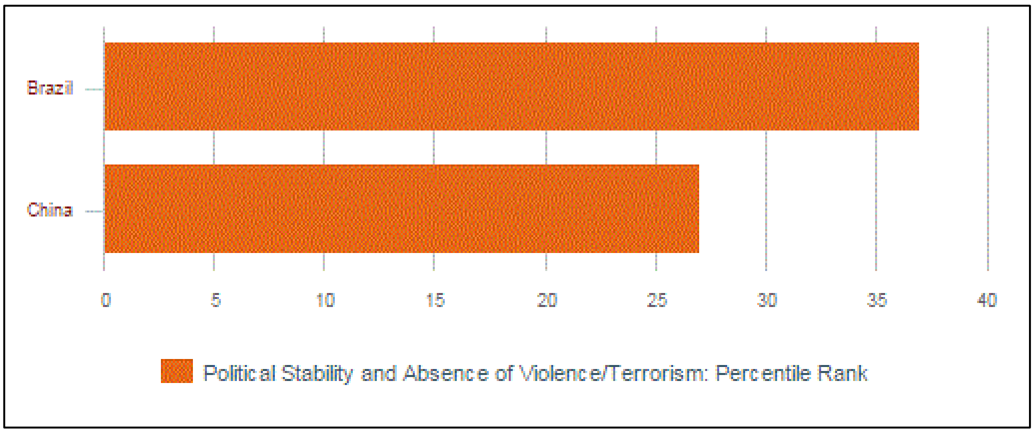

Figure 1. Political stability indicators for Brazil, China and Russia. Data from the World Bank after Kaufmann *et al.* (2010).

Companion metal fraction

Many critical metals are not mined on their own but are instead the by-product of mining of more common ores, such as aluminium, copper and zinc, in which they occur as trace constituents. By-product or companion metals typically have a greater risk of supply disruption because the infrastructure to recover these metals is often not established. The production of these metals is also particularly sensitive to prevailing economic conditions that impact on the host metal. The companion metal fraction is defined by Graedel *et al.* (2015) as: 'the percentage of a metal that is mined as a by-product'. The companion metal fractions used here were derived from Graedel *et al.* (2015).

Metals with a companion fraction of <33.3 per cent were scored one, those with a percentile between >33.3 and 66.6 per cent were scored two and those with a percentile of >66.6 per cent were scored three.

The scores were allocated as follows:

1 (low) = <33.3 %
2 (medium) = >33.3 to 66.6 %
3 (high) = >66.6 %

For example, indium is a by-product of zinc mining with approximately 95 per cent of global indium production (c. 500 tonnes) originating from the electrolytic refining of zinc, giving it a score of three. In contrast the production of copper is largely from primary copper mines, resulting in a score of one.

Supply risk

An integrated supply risk was calculated by combining the scores for each of the seven criteria. This is illustrated for two elements, rare earth elements and copper, in Table 2.

Category	**Rare earth elements**		**Copper**	
	Value	**Score**	**Value**	**Score**
Recycling rate (%)	<10	3	>50	1
Substitutability	0.87	3	0.56	2

Reserve distribution (%)	42	2	30	1
Production concentration (%)	96	3	32	1
Political stability (top reserve holder)	27	3	60	2
Political stability (top producing country)	27	3	60	2
Companion metal fraction	>66	3	<33	1
Total		**20**		**10**
Supply risk index (total/2)/(21*20)		**9.5**		**4.8**

Table 2. The calculation of a supply risk index.

Aggregate scores were normalised (Table 2) to produce a simple supply risk index from one (very low risk) to ten (very high risk). For example, copper has an initial aggregate score of ten. This is normalised to give a score of 4.8. This shows that copper has a lower relative risk to supply compared to REE with a score of 9.5. Below is the final ranked output list with gradational colour scale such that increased risk is indicated by hotter colours (Table 3).

Element	Rank	Top producer	Top reserve holder
REE	9.5	China	China
Sb	9.0	China	China
Bi	8.8	China	China
Ge	8.6	China	
V	8.6	China	China
Ga	8.6	China	
Sr	8.3	China	China
W	8.1	China	China
Mo	8.1	China	China
Co	8.1	DRC	DRC
In	8.1	China	
As	7.9	China	
Mg	7.6	China	Russia
PGE	7.6	South Africa	South Africa
Li	7.6	Australia	Chile
Ba	7.6	China	China
Graphite	7.4	China	China
Be	7.1	USA	
Ag	7.1	Mexico	Peru
Cd	7.1	China	
Ta	7.1	Rwanda	Australia
Re	7.1	Chile	Chile
Se	6.9	Japan	China
Hg	6.9	China	
F	6.9	China	South Africa
Nb	6.7	Brazil	Brazil
Zr	6.4	Australia	Australia
Cr	6.2	South Africa	Kazakhstan
Sn	6.0	China	China
Mn	5.7	China	South Africa
Ni	5.7	Indonesia	Australia
Th	5.7		USA
U	5.5	Kazakhstan	Australia
Pb	5.5	China	Australia
Fe	5.2	China	Australia

Diamond	5.2	Russia	Australia
Ti	4.8	Canada	China
Cu	4.8	Chile	Chile
Zn	4.8	China	Australia
Al	4.8	Australia	Guinea
Au	4.5	China	Australia

Table 3. The relative supply risk index. Risk is scaled between 1 (blue) and 10 (red), hotter colours indicate a greater risk to supply.

Limitations to the methodology

Previous studies of this nature by other researchers have included information pertaining to the environment, supply and demand, total material requirements (TMR), and climate change. This study omits many of these factors. For instance, we have not considered the potential impact of supply disruptions e.g. there is little demand for mercury, therefore the impact would be less than for an interruption to the supply of platinum group elements.

IMPORTANTLY - this represents a 'snapshot' in time and does not take into account future issues and supply-demand scenarios. The minerals market is not static, new reserves are continually added in response to drivers such as demand and advances in technology. In the future recycling is likely to contribute an increasing share to the global market and substitutability may also increase as new technologies are delivered.

Where more than one mineral source exists for a given element e.g. titanium occurring in rutile, leucoxene and ilmenite, all sources have been combined to give a total. Where appropriate, groups of elements have also been combined and dealt with as a single commodity e.g. platinum group elements and rare earth elements.

Certain commodities have been used as a proxy for a given element; this approach may mean that not all sources of an element have been included in the production and reserve calculations (Table 4).

Element	**Proxy**
Fluorine	Fluorspar - CaF_2
Carbon	Coal, diamonds, and graphite
Barium	Barytes - $BaSO_4$
Beryllium	Beryl - $Be_3Al_2(SiO_3)_6$
Titanium	Rutile and Ilmenite - TiO_2 and $FeTiO_3$
Magnesium	Magnesite - $MgCO_3$
REE	Rare earth oxides (REO)

Table 4. Proxy data used in the calculation of production and reserve concentrations for selected elements.

Where primary production data for a given commodity is limited other sources of data have been included (Table 5).

Element	Data Source
Indium	BGS estimates
Gallium	USGS production 'capacity'
Germanium	U.S. imports
Thorium	Monazite concentrate production
Selenium	Selenium metal production

Table 5. Sources used where production data for a given commodity are limited or non-existent.

Mineral resources[3] have been omitted from this study as there are no reliable comprehensive data on distribution or volumes.

Elements that have little or no commercial use have been omitted from this study e.g. polonium, astatine, and radium. Likewise, synthetic or 'manufactured' elements have also been omitted e.g. elements of atomic number 95 to 114, and hydrogen. Elements naturally occurring in a gaseous state are not included e.g. the noble gases, oxygen and nitrogen because the criteria used are unsuitable for assessing the supply risk of these elements. Production and reserve information for some of the minor metals e.g. scandium, yttrium, caesium, tellurium, thulium, and rubidium is unavailable because they are commonly produced as by-products or co-products of other metals. For example, yttrium is often associated with rare earth element-bearing minerals; scandium is found in trace amounts in minerals such as beryl, garnet and wolframite; caesium is often a by-product of lithium extraction; and tellurium, along with selenium, is a common by-product of nickel and copper ore extraction.

Definitions

1. *Reserves* - a 'mineral reserve' is the part of the resource which has been fully geologically evaluated and is commercially and legally mineable. Reserves may be regarded as 'working inventories', which are continually revised in the light of various 'modifying factors' related to mining, metallurgy, economics, marketing, law, the environment, communities, government, etc. (USGS, 2010).

2. *Resources* - a 'mineral resource' is a natural concentration of minerals or a body of rock that is, or may become, of potential economic interest as a basis for the extraction of a mineral commodity. A resource has physical and/or chemical properties that make it suitable for specific uses and it is present in sufficient quantity to be of intrinsic economic interest. It encompasses 'mineral reserve' and 'reserve base' plus other identified resources which could be exploited in the future if required according to the economic situation (USGS, 2010).

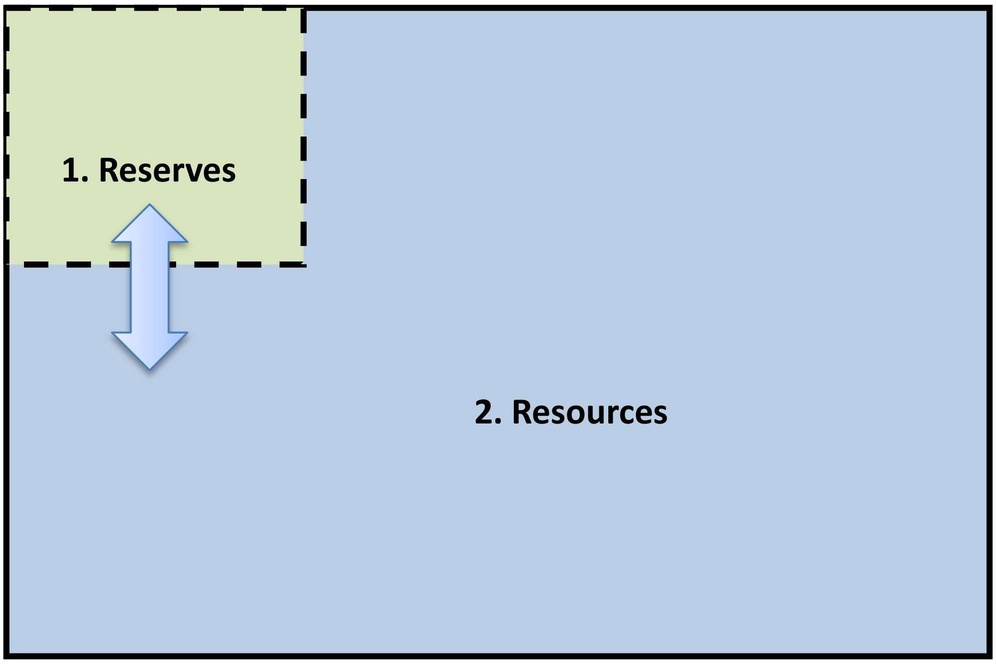

Figure 3 - Graphical representation of the relationship between reserves and resources.

References

Achzet, B., Reller, A. and Zepf, V. (University of Augsburg), Rennie, C. (BP), and Ashfield, M. and Simmons, J. (ON Communication) (2011): *Materials critical to the energy industry: an introduction.* Available: http://www.bp.com [accessed July 2015].

European Commission. (2010). *Critical raw materials for the EU - Report of the Ad-hoc Working Group on defining critical raw materials.* Available: http://ec.europa.eu [accessed July 2015].

Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P. and Reck, B.K. (2015). *Criticality of metals and metalloids.* Proceedings of the National Academy of Sciences of the United States of America (PNAS) 112 (14), 4257-4262.

Kaufmann, D., Kraay, A. and Mastruzzi, M. (2010). *The Worldwide Governance Indicators: Methodology and Analytical Issues*. World Bank Policy Research Working Paper No. 5430. Available: http://info.worldbank.org [accessed July 2015].

UNEP (2011). Recycling Rates of Metals – A Status Report. A report of the Working Group on the Global Metal Flows to the International Resource Panel. Graedel, T.E., Allwood, J., Birat, J.P., Reck, B.K., Sibley, S.F., Sonnemann, G., Buchert, M. and Hagelüken, C. Available: http://www.unep.org [accessed July 2015].

United States Geological Survey. (2014 and 2015). *Mineral Commodity Summaries [online].* Available: www.usgs.gov [accessed July 2015].