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A dynamic perspective of the geopolitical supply risk of metals

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ABSTRACT

Metals are distributed in the earth's crust in varying amounts and ore concentrations, implying that some countries have more metal resources than others. This inequality in geological resource distribution may lead to potential constraints and bottlenecks of a steady resource supply. In the context of strategic planning and innovation, and in scientific literature, this aspect is often referred to as *geopolitical supply risk*. In the past few decades, cobalt crisis, the oil embargo, and the more recent Rare Earth Elements (REEs) issue are the best examples regarding the geopolitical supply risk of mineral resources. The aim of this study is to present a historical overview of the development in geopolitical supply risk of 52 metals during the past two decades and to support an assessment of such risk in the future, i.e. 2050. A geographical mapping of metals primary production in 1994 and 2013 is included which shows a shift from developed economies to developing economies over this time period. Our analysis demonstrates that the geopolitical supply risk of metals has been fluctuating during the past two decades due to change in the number and production share of producing countries. During this time period, Chinese share of global metals production has increased from 23% to 44%. China, today, is also the dominant supplier of 34 metals, out of which 23 are considered as *critical resources* by the European Commission. The future geopolitical supply risk is less dependent on the present production distribution and more dependent on the location of current geological resources and the future discoveries, as well as on the technological development to improve profitability of mining the currently sub-economical resources.

1. Introduction

The Modern society depends on metals. Metals are the basis of our infrastructure and the technology, without which it is hard to imagine modern life. Metals are non-renewable by nature as they have been generated as a result of geological events spanning over hundreds of millions of years, which makes them a finite resource. Nevertheless, metals do not disappear after their consumption *per se* like some other resources especially fuel minerals e.g. oil, gas and coal due to their non-dissipative nature. This means that metals can be reproduced by recycling them from urban mines, though with the product's long lifetimes and economic implications. Despite the fact that the geological resources of metals are finite, their unprecedented extraction from the earth especially during the last two centuries has raised concerns regarding their long-term availability to meet the demand of future generations (Bardi, 2014; Prior et al., 2012). Simultaneously, we have witnessed the substantial growth of economically viable geological reserves[1] of these metals over time, which has been made possible by the advent of modern technology making the once very expensive to mine lower ore grade resources to be exploited economically today (Habib and Wenzel, 2014). Within the context of secure, uninterrupted, and long-term availability of resources, a relatively new research field of *resource criticality assessment* got widespread popularity during the recent years (Habib and Wenzel, 2016).

A critical resource is considered to be one which is significantly important for the functioning of a system i.e. a technology, company, nation or the whole world, and at the same time is subject to high level of supply risk. Supply risk further can be assessed with the help of a number of constrained parameters or indicators, where the two most commonly used indicators are geological and geopolitical supply risk of a particular resource. *Geological supply*

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[1] According to the USGS, Reserve is that part of reserve base (part of the total geological resource of a metal) which could be extracted or produced economically at the point of determination (Source: http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcsapp2009.pdf).

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risk is often represented with the help of reserve to production ratio, which shows the lifetime (number of years) of currently known reserves. Another important parameter of geological supply risk is the share of a resource produced as a by-product of some main product, e.g., molybdenum is mainly produced as a by-product of copper. This reflects the concern regarding market ability to meet a sudden increase in demand if the resource in question is mainly produced as a by-product (Habib, 2015).

In recent history, the nature of supply risk for metals has shifted from geological availability/scarcity to more geopolitical availability/scarcity. *Geopolitical supply risk* addresses the risk of potential supply disruptions caused by a single or few countries controlling the market of a particular metal and the level of political stability in such countries (Habib and Wenzel, 2016). The cobalt supply disruption in late 1970s, the palladium supply restriction in late 1990s, and the Rare Earth Elements (REEs) issue in 2010–2011 are good examples of geopolitical factor of metals supply risk. The detail of these resource disruptions is presented in the following section.

1.1. *Resource supply disruptions from the 1970s until present*

1.1.1. *The cobalt supply disruption in the 1970s*

The cobalt (Co) supply restriction in 1978 is a good example of the limited availability of a metal due to supply disruptions, and its consequences for society. Cobalt is a metal of strategic importance and is used in both industrial and defence related applications. The major uses of cobalt are superalloys which are further used in aircraft engines, magnets, cemented carbides, cutting tools and other chemical industry applications (Habib, 2015; Harper et al., 2012; USGS, 1999a). Cobalt has been identified as a critical resource to the European Union due to the concerns related to its supply risk and economic importance (European Commission, 2014, 2010).

During the early 1970s, the Democratic Republic of Congo (then called Zaire) and the neighbouring country Zambia were in control of almost two thirds of the global cobalt production. In 1978 there was political instability in the Democratic Republic of Congo which resulted in slowing down of mining activity. Meanwhile, the demand of cobalt increased sharply due to an upsurge in the global economy. Thus, the gap between demand and supply coupled with the delayed transport of cobalt from the producing countries to the Western world resulted in price speculation. The price of cobalt increased fivefold from \$11,880 Mg^{-1} in 1976 to \$55,000 Mg^{-1} in 1979 (Habib, 2015; Alonso, 2010).

The supply constraints of cobalt had a wide range of implications for the industry and governments. This forced the stakeholders to find solutions such as reducing the use of cobalt, finding substitutes in key applications, diversifying the primary supply by increasing production of cobalt in other countries, and building stockpiles for defence related uses. As a result of the crisis, the substitution possibility of cobalt was taken very seriously, which is visible from the decreased consumption of cobalt in permanent magnets which were significantly displaced by the newly developed ferrite magnets. The total consumption of cobalt for permanent magnets dropped from 30% before the crisis to 10% after the crisis (Wagner and Wellmer, 2009). Furthermore, the recovery of cobalt from the scrap superalloys doubled (Alonso, 2010; USGS, 1999a). The cobalt supply disruption demonstrated the importance of having a more diverse supply of resources instead of a near-monopoly situation, in order to minimize the implications of potential supply constraints for different stakeholders. For example, immediately after the cobalt crisis, Zambia and Australia increased the production of cobalt to reduce the dominance of the Democratic Republic of Congo over global primary supply. Further, it provided incentives to industry to increase the recovery rate of cobalt from the scrap material and, thus, reduce the dependence on primary supply. Moreover, the mining and refining companies improved their processes to reduce process losses and enhance the recovery of cobalt from its ores (Habib, 2015; Alonso, 2010).

1.1.2. *The palladium supply disruption in the 1990s*

Palladium (Pd) belongs to the precious metals group i.e. platinum group metals (PGMs), which are mainly used as catalysts in the automobile sector for pollution abatement. Other uses of PGMs are in fuel cells, petroleum refining, chemical industry, electronics, glass manufacturing, medical appliances, jewellery, and as investment (USGS, 2012a). The leading use of palladium is in automobile catalysts, which corresponded to almost 72% of total palladium consumption in 2013 (Cleantech VWS, 2014). In 1997, the U.S. Environmental Protection Agency's introduced and voluntarily implemented the National Low Emission Vehicle (NLEV) Program, which got federally mandated in 2001. This law emphasized lowering hydrocarbon emissions from the automobile sector, and thus enforced the use of catalytic converters to reduce emissions. This further led to an increased demand of palladium in catalytic converters for the gasoline-fuelled vehicles (Habib, 2015; USGS, 2012a).

During the late 1990s, a supply disruption of palladium was experienced, because Russia in 1997 reduced the exports of palladium by nearly 65%, while remaining the major producer with a 43% share of global production. Meanwhile the demand for palladium had skyrocketed within the automotive industry (38% annual growth) due to the enactment of NLEV program in the same year. The significant supply shortfall led to an enormous increase in the price of palladium from 1997 to 2000, which further resulted in dramatic changes in demand of palladium. The total demand of palladium in 2002 dropped by 50% compared to the demand in 1999. Even though the demand grew afterwards, it was still lower in 2007 compared to 1999 (Alonso, 2010; Johnson Matthey Precious Metals Management, 2008). Another response from the demand side was to diversify the supply by increasing the production capacity in other countries such as Canada, South Africa and Zimbabwe (Habib, 2015).

1.1.3. *The rare earth elements supply disruption during the recent years*

The most recent example of metals supply disruption is of REEs. The REEs group consists of lanthanide series consisting of 15 elements (atomic number 57–71) plus scandium (atomic number 21) and yttrium (atomic number 39) (Kirk-Othmer, 2005; Ulmanns, 2005). REEs have unique physical and chemical properties which make them highly attractive in many of today's high-tech applications e.g. permanent magnets containing neodymium and dysprosium. The performance level provided by these magnets in terms of their magnetic strength allows significant size and weight reduction in many of today's modern applications while maintaining the same performance level. These magnets are widely used in computers, audio systems, electric and hybrid vehicles, cell phones, wind turbines, Magnetic Resonance Imaging (MRI) machines, and others (Habib et al., 2014, 2015).

From 2005 to 2010, China has been the dominant producer with 97% share of the global REEs production. During the same period, the Chinese government kept shrinking the export quota of REEs to the rest of the world, where this quota had reduced by almost 53% from 2005 to 2011 with the most significant reduction from 2009 to 2010, which alarmed the industrial players and governments alike (Habib and Wenzel, 2014). China reduced the export of REEs to the rest of the world in order to prioritize the domestic demand and to increase the production and export of high value goods using REEs e.g. permanent magnets, motors, and batteries (Habib, 2015).

Due to the industrial and strategic measures taken by the Chinese government, the global market experienced the ever highest prices of REEs in 2011. This rapid increase in price led governments and industry to seek other solutions, including stockpiling, investing in mines outside China, replacing REEs by other elements, and increasing recycling rates (Machacek and Fold, 2014). The immediate response to this supply disruption imposed by China was opening of new mines outside China and bringing REEs production online. This has led to reduce the Chinese share of global REEs production from 97% in 2010 to 87% in 2014. The remaining 13% is supplied by the USA, Australia, India, Brazil, Malaysia, and other countries (Habib, 2015; USGS, 2013).

1.1.4. Key lessons learnt from the cobalt, palladium, and rare earth elements supply constraints

As documented in Habib (2015), there are a number of lessons which can be learnt from the above mentioned cobalt, palladium and rare earth elements supply crises:

- The underlying reason behind all the three resource supply crises has been of geopolitical nature, where only a few countries were controlling the global supply and the supply disruptions were imposed by restraining export from the dominant producing countries, and due to the political stability and governance issues of the producing countries.
- The immediate result of such a supply disruption has resulted into skyrocketed prices within a short time, which has forced the industry to cut short the demand of resource in question by looking for the opportunity to completely avoid or minimize the required amount of resource, and find other easily available substitutes.
- Another response has been increased investment by the stakeholders in research and development (R&D) programs to find the efficient recycling and recovery techniques of such resources from the waste streams.
- The other measures include enhancing the production capacity of existing facilities and opening of new mines in other countries than the dominant producers to diversify the supply, and thus reduce the risk of supply disruption in medium-to-long term future.

1.2. The aim of this study

The above mentioned examples of resource supply constraints were mainly caused by the geopolitical issues, and were temporary in all cases. The immediate effect of the supply disruption was in all cases market price oscillation, i.e., a steep price increase that in all cases after a period (of 5 years for cobalt and palladium, and 2–3 years for rare earth elements) dropped back to the price level, it had before the increase (Habib, 2015). A recent study by Buijs et al. (2012) has documented the dynamic nature of geopolitical supply risk with the help of Herfindahl Hirschman Index (HHI, detail can be found in Section 2) for a few metals from 1996 to 2009. There are studies that have focused on the regional patterns of different material production such as biomass, fossil fuels, metals, industrial and construction minerals (Schandl and Eisenmenger, 2006) as well as their global flows over a certain period of time (Schaffartzik et al., 2014). Bruckner et al. (2012) have considered the global material extraction and consumption trends by regions from 1995 to 2005. Though the above mentioned studies provide a comprehensive overview of the global metabolic trends by region and their transition over time for a range of materials, they have not focused exclusively on metals in detail.

In this study, we aim to provide a historical overview regarding the geopolitical supply risk of 52 metals primary production (mining output) from 1994 to 2013, and further estimate this risk for 2050 in order to visualize the potential geopolitical supply risk of metals in future. It is also our aim to show the geographical shift of metals primary production during the past two decades with the help of global maps. The process of metals primary production comprises several steps. For example in case of REEs, the primary production consists of processes like mining, beneficiation, cracking and chemical separation (Machacek and Fold, 2014). The scope of this study is limited to only the first step of the whole value chain of metals primary production i.e. mining output. This is because mining has to take place at the site of resource location, where the other subsequent steps can be performed in countries without having that resource geologically – depending of course on the technologic, economic and other conditions. In this manuscript, we refer to mining while stating primary production.

2. Estimating the geopolitical supply risk of metals

To estimate the geopolitical supply risk of metals considering their primary production (mining) from 1994 to 2013, a widely accepted parameter called Herfindahl Hirschman Index (HHI) has been chosen. Habib and Wenzel (2016) have shown that the majority of resource criticality assessment studies have considered HHI to show the potential supply risk originating from a highly concentrated supply situation. This index is named after two well-known economists, Albert O. Hirschman who introduced it back in 1945 for the first time, and Orris C. Herfindahl who reinvented it in 1950 (Hirschman, 1980). HHI is a measure to analyse the market concentration and is calculated by summing the square of market share of each country (%):

$$HHI = \sum_{i=1}^{N} (S_i)$$

where S_i is the share of country i in the market and N is the number of countries.

The highest score at HHI scale is 10,000 indicating a monopoly market (only one country having 100% market share). The HHI score increases due to a decrease in number of countries as well as increase in their size or market share. According to the U.S. Department of Justice and the Federal Trade Commission (2010) guidelines, the HHI score between 1500 and 2500 is considered as moderately concentrated market and the score above 2500 reflects highly concentrated market.

In the current study, to calculate the HHI of 52 metals from 1994 to 2013, we have collected the global primary production data for each metal, using the so far most comprehensive database developed by the U.S. Geological Survey (USGS, 1996–2014). Furthermore, in order to estimate the HHI of different metals for the year 2050, we have used the current geological reserve estimates reported by the U.S. Geological Survey (USGS, 2014) for each of the metal considered in this study by assuming that it represents the future primary supply share of countries for the relevant metals. Although these HHI estimates provide useful information regarding the metals that might face supply constraints in the medium-to-long term future, we have moved a step forward to show the geographical shift in global metal's primary production (mining) by different countries over two decades (from 1994 to 2013) on the global map with the help of commonly used software tool MapInfo Professional version 12.0 (2014).

3. The development in geopolitical supply risk of metals

Results are presented as per the groups of metals (see Table 1) defined in UNEP (2011). Fig. 1 presents the estimated HHI score of metals considered in this study from 1994 to 2013, and for the year 2050.

i. Ferrous metals – In general, the metals contained in this group have historically lied in low-to medium risk categories (HHI score 0–4000), except Nb, which is mostly used as an alloying element to enhance the strength of steel. Nb has always been subject to high geopolitical supply risk, where its HHI score has raised from 7288 in 1994 to 7977 today (see Fig. 1). This is because in 1994 Brazil was producing 84% of the global Nb and almost 15% was produced by Canada, whereas today Brazil supplies 89% of Nb and Canada is responsible for almost 10% of the global Nb supply. However, the geopolitical supply risk of Nb is likely to get even worse in future i.e. by 2050 because almost 95% of the global currently known geological reserves are present in Brazil, and the remaining 5% are in Canada. This gives Nb an HHI score of 9113 which signals a near monopoly market situation in future for Nb. However, the overall trend is subject to change in case of any geological resource discoveries and opening of new mines around the world in future. The detailed data regarding different metals in this group can be seen in the Supplementary material of this article.

ii. Non-ferrous metals – Like the ferrous group metals discussed above, metals in this group also seem to have low-to-medium level of geopolitical supply risk. Apart from Co which has been discussed in detail in Section 1.1.1, Cu is a metal of high interest since it is one of the very first metals extracted by human beings. It offers high electrical and thermal conductivity which makes it crucial for everything operating on or transmitting electrical current (Bardi, 2014). Our results show that during the past two decades, Cu has not faced any geopolitical supply constraints despite the fact that a single country, Chile had produced 24% of the global Cu supply in 1994 whereas today it has increased to 32%. The current low geopolitical supply risk shown with the help of HHI score of 1366 in Fig. 1 is mainly because the rest of Cu supply is highly dispersed across the globe. Moreover, by looking at the current known geological reserves of Cu, it becomes clear that Chile has 28% of the Cu geological reserves. The second largest reserves of Cu i.e., 13% are present in Australia, while the rest of reserves are widely distributed among different countries. This means that Cu is unlikely to face any geopolitical supply risk even in future.

This group contains Al which is the most abundant metal in the earth's crust. The geopolitical supply risk of Al has always been in the low-to-medium risk categories, though the HHI score has increased considerably from less than 1000 in 1994 to almost 2270 today. This increase in HHI of Al has been primarily due to the Chinese rise in Al production from 0% in 1994 to almost 45% of the global supply today. Due to the data limitations regarding the geological reserves of Al, it is hard to estimate the future HHI score for Al. The detailed primary production and geological reserve data for all the elements in this group can be found in the Supplementary material.

iii. Precious metals – As the name suggests, this group consists of precious metals out of which Au and Ag were probably the first metals ever extracted on earth (Bardi, 2014), whereas the Pt group metals such as Pt and Pd are increasingly finding their role in modern products especially auto catalysts used in the emission control system of passenger vehicles. These elements are also used in jewellery. Au and Ag, both have high electrical conductivity which makes them highly desirable in modern electronics apart from their historical use as investment and jewellery. Our results regarding the geopolitical supply risk assessment of Au and Ag show that these two metals have not faced any such risk during the past two decades (see Fig. 1). This is because the production of these precious metals is widely distributed across the globe where Chile is currently the dominant producer of Au with only 15% of the global supply, whereas Mexico is the leading producer of Ag with 21% of the global supply. Furthermore, our results reveal that these two metals do not seem to face any geopolitical supply risk in the medium-to-long term future i.e. by 2050 because the geological reserves of these precious metals, like their primary production, are quite widely distributed across the earth's crust. In contrast to Au and Ag, the Pt group metals especially Pt has been through medium-to-high level of geopolitical supply risk, though, the risk has decreased during the last two decades. This is mainly because in 1994, South Africa was producing nearly 80% of the global Pt which has reduced to 73% today. The second largest producer of Pt has always been Russia with nearly 12% of global supply in 1994 and 13% today. Our results further reveal that in future the geopolitical supply risk of Pt group metals seems to get worse because 95% of the current known geological reserves are present in a single country, South Africa.

iv. Speciality metals – Speciality metals group refers to the group of metals which are used in very small quantities in their end-use products and have a very specialized function to perform due to their specific physical and chemical properties. In this group, REEs have been of increasing interest over recent years (see Section 1.1.3 for more details). Li has received more attention especially during the last decade because of its important role in batteries for eco-friendly vehicles such as Electric Vehicles (EVs), and Plug-in Hybrid Electric Vehicles (PHEVs). Consequently, the long term availability of Li is

Table 1
Group of metals considered in this study.

Group no.	Group name	Metals
I	Ferrous metals	Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickle (Ni), Niobium (Nb) and Molybdenum (Mo)
II	Non-ferrous metals	Magnesium (Mg), Aluminium (Al), Titanium (Ti), Cobalt (Co), Copper (Cu), Zinc (Zn), Tin (Sn) and Lead (Pb)
III	Precious metals	Palladium (Pd), Silver (Ag), Platinum (Pt) and Gold (Au)
IV	Speciality metals	Lithium (Li), Beryllium (Be), Boron (B), Germanium (Ge), Arsenic (As), Selenium (Se), Strontium (Sr), Yttrium (Y), Zirconium (Zr), Cadmium (Cd), Indium (In), Antimony (Sb), Barium (Ba), Rare Earth Elements (REEs),[a] Tantalum (Ta), Tungsten (W), Rhenium (Re), Mercury (Hg) and Bismuth (Bi)

[a] REEs are a group of 15 elements from the lanthanide series plus scandium and yttrium. In this study, data regarding the primary production (mining) from 1994 to 2014 considers REEs as the 15 elements from the lanthanide series, where yttrium is considered separately due to detailed data availability, and scandium is not taken into account for data availability issues. However, the geological reserve data of REEs considers REEs as a group of 15 elements from the lanthanide series plus scandium and yttrium.

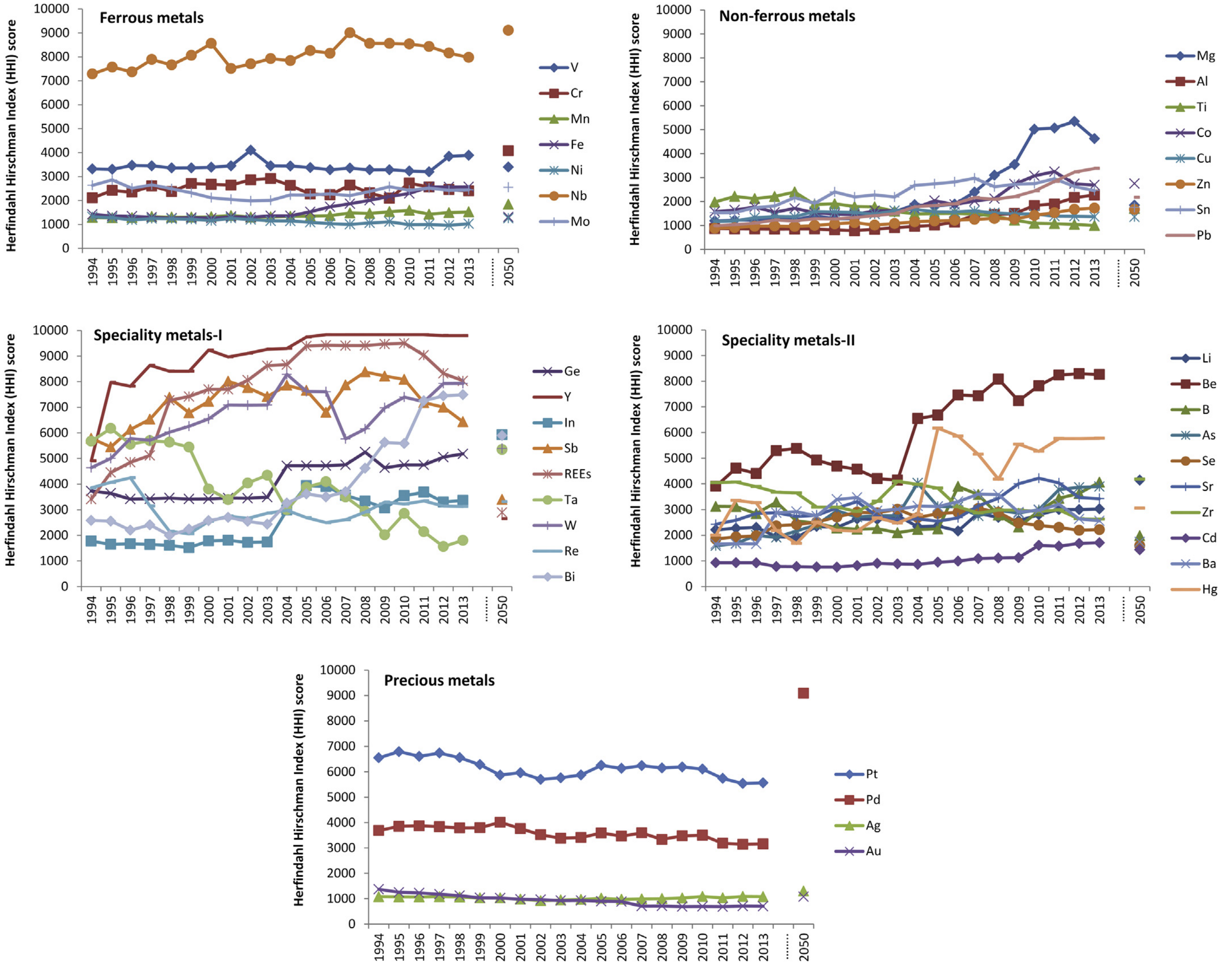


Fig. 1. The estimated Herfindahl Hirschman Index (HHI) score representing the risk of concentrated supply for four groups of metals considered in this study from 1994 to 2013 based on the mining data, and for 2050 considering the current geological reserve share of metals by countries being representative of future primary supply share.

important issue (Speirs et al., 2014; Vikström et al., 2014). Our results show that over last two decades, the HHI score of Li has increased from nearly 2200 in 1994 to 3000 today. This is because in 1994 Chile was the dominant supplier with 33% share of the global supply and Australia was the second largest supplier with nearly 28% share, whereas today Chile and Australia are producing 38% and 37% of the global Li supply, respectively. Furthermore, our results show that the geopolitical supply risk of Li seems to increase in future to 4000 HHI score, because almost 58% of the current known geological reserves of Li are in Chile and 27% in China. The detailed data regarding the global primary supply of other metals in this group can be found in the Supplementary material.

In general, it can be clearly seen from Fig. 1 that the global supply of the ferrous and non-ferrous metals is considerably less concentrated compared to majority of the speciality and precious metals. This is because the geological reserves and mining of ferrous and non-ferrous metals are distributed across the globe, whereas the known reserves and production of most of the speciality and precious metals are concentrated in a few countries. This means that the speciality and precious metals are prone to a higher supply risk compared to ferrous and non-ferrous metals.

4. The role of recycling in lowering the future geopolitical supply risk of metals

Recycling of metals, in particular the so-called “critical metals” such as REEs has gained wide attention during the recent years, where some studies in particular have focused on the role of recycling in lowering the geopolitical supply risk (Habib, 2015; Habib and Wenzel, 2014, 2016). Theoretically, recycling can play significant role in lowering the future geopolitical supply risk of metals because unlike the primary supply, the secondary supply originating from recycling activity is not geographically fixed in the form of minerals containing ores present in particular geological formations across the earth's crust. In other words, secondary supply may originate from the countries having no geological reserves of a particular metal due to imports of such metals or their end-use products from the resource rich or other manufacturing countries. However, recycling may also face technical and logistic constraints in future. This concern is very much true for the speciality metals (as described in Section 3) because these metals are produced in lower volumes compared to the bulk metals such as Fe, Al, Cu etc., and are used in very small quantities in their final product e.g., a smart phone may contain maximum 2 g of REEs such as Nd and Dy for specific functionalities in different components of the phone. So, the end-of-life recovery of these speciality metals from different components found even in one specific product type is quite challenging, making them hard to recover in an economically feasible manner. Moreover, most of these speciality metals have less than 1% recycling rate today, and to our knowledge, there are no proven commercial scale technologies to recover these speciality metals such as REEs from a wide array of end-of-life products (Habib et al., 2015, 2014).

The usual long lifetimes of the end-use products of these metals e.g., wind turbines and passenger vehicles delay their recovery from two to three decades. Apart from these issues, there are concerns regarding the global secondary supply share in future where it is most likely that the developing countries such as China, who are consuming big shares of today's resource production (Muradian et al., 2012; Schaffartzik et al., 2014) will generate the future secondary supply. This, of course, does not help the issue of geopolitical supply risk especially when the given country is already the dominant supplier of a resource primary production. This whole debate underlines the importance of detailed mapping of metals especially the critical ones, across the globe, in order to be certain about the scale of secondary production as well as their geographic origin in future. This is an interesting subject for future work.

5. Geographical shift of metals primary production

In the previous section, we described the dynamic nature of geopolitical supply risk of metals based on primary production (mining output) data with the help of HHI. Though it provided useful information regarding the changing intensity of current and future geopolitical risk, it does not reveal much about the geographical transition of metals primary production over the past two decades. This section is aimed at providing a holistic overview of geographical transition regarding the primary production of the 52 metals considered in this study, as well as the supply trends of so-called critical metals from 1994 to 2013.

5.1. Geographical transition of metals primary production, 1994–2013

During the past two decades, the geographical patterns of primary production of metals have changed significantly. Fig. 2 presents the global map with the major metals producing countries in 1994 and 2013, where it becomes clear that the countries such as the USA and Russia which were once responsible for almost 6% and 13% share of global supply of metals, are now producing only 2% and 3.5% respectively. On the other hand, the rising economic giant of Asia i.e., China has nearly doubled its share of global metals production from almost 23% in 1994 to 44% today. Bruckner et al. (2012) have also reported this expansion of Chinese metals extraction from 1995 to 2005. During the same period, global production of the metals considered in this study has increased by a factor of 3, from 1072 Tg (Tg = 10^{12} g) to approximately 3103 Tg.

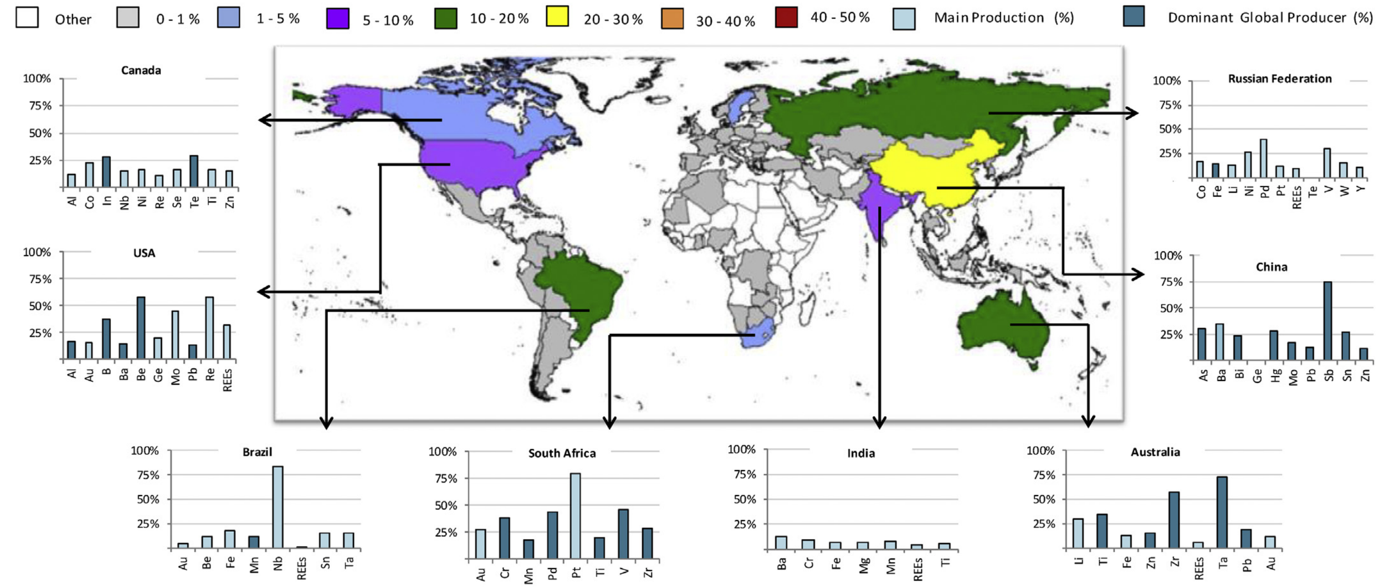
The exponential increase in Chinese share of global metals production has been primarily due to the cheap labour, and less stringent regulations regarding the social and environmental responsibility in China, which makes it cheaper to extract these resources and manufacture the final products in China. For this reason, many international companies have their production units based in China. However, it does not mean that whatever is extracted in China is exported to the rest of the world. In fact, over the past two decades China has become the largest importer of non-fuel mineral resources such as metals (Muradian et al., 2012). Chinese domestic demand for all these metals has grown over time, making China the biggest consumer of metals today. In 1997 China consumed almost 10% of the global iron production, which 10 years later has increased to 45% (Buijs and Sievers, 2012a,b). Though China is producing 44% of the global metals supply and is a major consumer of these metals, the overall per capita consumption of resources (9 Mg/capita/year) is still far behind the developed countries such as the USA and other western countries with almost 15 Mg/capita/year consumption (Muradian et al., 2012; Schaffartzik et al., 2014). This gap in per capita consumption of resources between the developing countries such as China and the developed countries suggests a continuous increase in the future extraction and consumption of these resources by the developing countries.

Despite the fact that global metals production has increased by a factor of 3 from 1994 to 2013, Russian domestic extraction of these metals has decreased from almost 139 Tg to 108 Tg over the same time period. The primary reason for this is the dissolution of former Soviet Union in 1991 followed by the dramatic reduction in extraction and use of these resources (Schaffartzik et al., 2014). Apart from Russia, the USA has also shown a decreasing trend in the global production share of metals from almost 6% in 1994 to nearly 2% in 2013, where the production of metals by USA has decreased from 66 Tg to 57 Tg during the past two decades. This decrease in domestic extraction and production of metals can be attributed to the increasing imports of metals by the USA mainly from Canada, Asian and Latin American countries (Muradian et al., 2012). Furthermore, the global metals production share of other major producing countries i.e. Australia, Brazil and India has been nearly constant during the past decades, although the production volumes have increased by a factor of 4, 2.4 and 2.7, respectively.

5.2. Supply trends of the critical resources, 1994–2013

Fig. 2 presents the results regarding the monopolistic supply of metals for the eight major metal producing countries for the years 1994 and 2013. Our results show that in 1994, China was the dominant supplier of at least 24 different metals (including REEs as a group of 15 metals) such as Mn (16%), Fe (24%), As (30%), Y (68%), Sn (27%), Sb (75%), Ba (35%), REEs (47%), W (65%), and Hg (28%). Today, China is a dominant producer of nearly 34 different metals (including REEs as a group of 15 metals) such as Mg (67%), Al (45%), V (53%), Fe (45%), Zn (37%), Ge (71%), As (56%), Y (99%), Mo (41%), Cd (34%), In (53%), Sn (44%), Sb (80%), Ba (45%), REEs (89%), W (89%), Au (15%), Hg (75%), Pb (56%), and Bi (86%). In Fig. 2, only 10 of these metals are shown for China due to the limited space, where the details of remaining metals can be found in the Supplementary information (Tables 1 and 2). Out of these 34 metals, some metals e.g. Al, Ge and Cd were not produced in China in 1994, though now China is the leading producer of these metals. Additionally, today China is the dominant producer of Au, which was not the case in 1994 where China produced only 7% of the global Au production, and South Africa was the dominant producer with 27% share which has now decreased to only 5%. On the other hand, though China has increased the share of its production of Mn from 16% in 1994 to 19% in 2013, it is no more the dominant supplier of Mn because South Africa is producing 23% of global Mn production. The recently published report by the European Commission (EU) on critical resources (European Commission, 2014) considers Mg, Ge, Y, In, Sb, REEs and W as critical resources for the EU where the primary production (mining) of all of these metals is dominated by China currently.

(a) 1994



(b) 2013

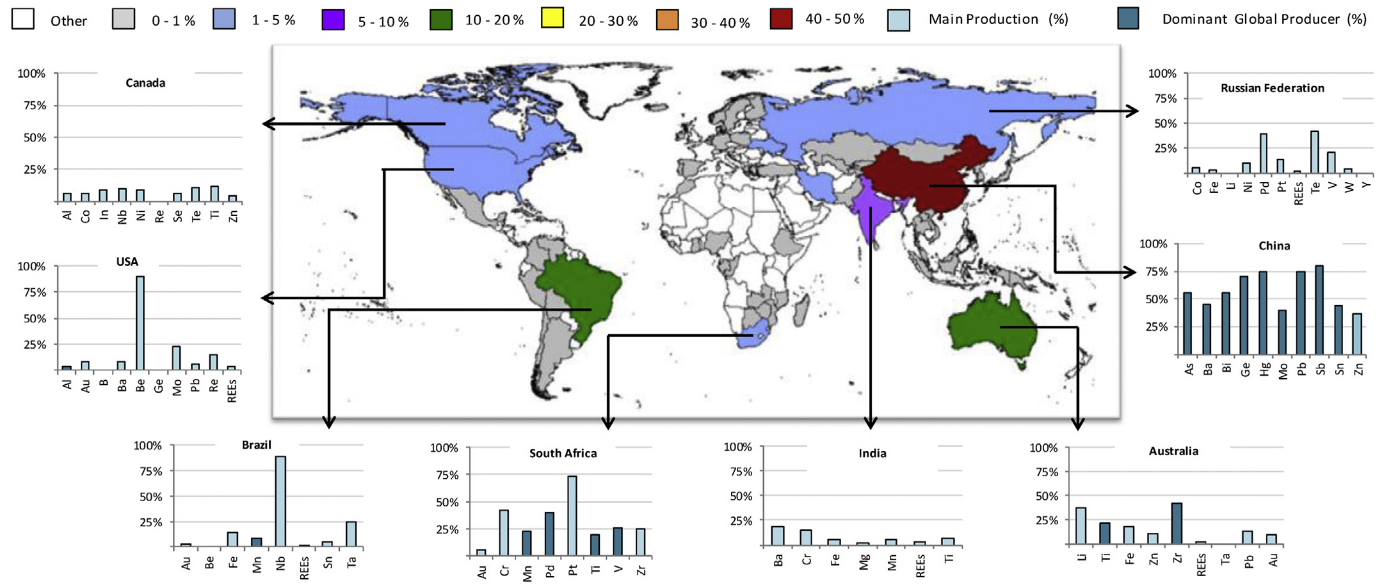


Fig. 2. Global share of metals primary production (%) in 1994 (a) and 2013 (b). The bar graphs show the share (%) of annual global production of main metals produced in selected countries, with the dark blue bars indicating metals with the highest share in annual global production. The colour of different countries on global map shows their respective share (%) in the annual global production of all metals considered in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Another interesting case is of South Africa, which has always been the dominant producer of precious metals such as Au, Ag, Pt and Pd. In 1994, South Africa produced 80% of Pt, 44% of Pd and 27% of Au global primary production. After two decades, South Africa is still the largest producer of Pt (73%) and Pd (39%) – considered as critical resources for the EU (European Commission, 2014).

5.3. *Future prospects regarding the primary supply of metals*

The recent REEs issue has largely led the potential stakeholders to concerns of having a secure and uninterrupted supply of resources in the future, raising the question “if today's dominant producers will remain the same in future too?”. To reach the answer is obviously not straight forward as we have very limited knowledge of future demand and supply dynamics for all of these metals, potential future mining projects in different countries, and the future environmental and socio-economic framework conditions in different countries producing these metals. However, we used the current known geological reserve estimates and their distribution in different countries as a proxy for potential producers in future to enhance our understanding of possible geographical transition of metals primary production in future.

Table 3 in the Supporting information shows the geological reserve distribution by countries for all the metals considered in this study, where it can be seen that Australia has the largest metals reserves equivalent to 18% of the global reserves. It has almost 21%

of the global iron reserves, equivalent to 96% of Australia's total reserves of metals. The second largest share of reserves is present in Brazil, i.e., 15% followed by Russia having 13%. This, in general, suggests that Chinese dominance over the metals production market is likely to decrease with time as the geological reserves of metals are widely distributed in the earth's crust. However, this seems not true for the so-called critical resources for the EU (2014) because China still holds majority of their reserves such as Y (40%), In (75%), Sb (52%), REEs (48%), and W (72%).

Though these estimates provide useful insights into the future geopolitical supply risk of metals, they should not be considered as the writing on the wall because the geological reserves of metals are dynamic entities. This means that reserves can increase over time resulting from new discoveries across the globe, technological developments, and changing economic conditions. It is worthwhile to mention here that unlike the historical trend (c.f. Habib and Wenzel, 2014), reserves cannot grow forever in future as the overall geological resources are finite entities, and are subject to depletion due to ever increasing production. Moreover, many of the metals today are produced as a co-product of some host metal. Their production is highly dependent on demand for host metal, availability of efficient separation and refining technologies, and economic feasibility – all of these aspects develop over time and are hard to predict for future. So, any of these factors can lead to a change in future metals production trend, and therefore influence the results presented in this study.

Traditionally, *risk assessment* is defined as a product of likelihood of an incident to happen and its impact/consequence on the system under consideration. The growing field of *resource criticality assessment* is analogous to *risk assessment* as it comprises two dimensions: first, probability/risk of supply disruption; and second, its impact/consequence for the selected system (Habib and Wenzel, 2016). The results presented in this study reflect the first dimension, i.e., supply risk, by estimating only the geopolitical supply risk with the help of HHI. It is worthwhile to mention that the HHI results basically highlight the degree of consequence by depending on more/less concentrated supply. The results do not show the probability/likelihood of the supply disruption to happen at the first point, which may take place because of stringent environmental legislation, social justice, governance conditions and other factors in a particular resource producing country.

6. Concluding remarks

In this study, we have analysed the geopolitical supply risk and the geographical transition trend of global primary production of 52 metals in 86 different countries from 1994 to 2013. We further projected this transition in future i.e., 2050 by using the global distribution of current known geological reserves (2014) of metals as representative of their global primary production share by countries in 2050. It is evident that the geopolitical nature of supply risk is a dynamic property because it fluctuates over time due to the changing share of production by countries, thus implying that the resources which are considered as critical today mainly due to their estimated high geopolitical risk are unlikely to face the similar situation in future unless their production and reserves are highly concentrated in a single or few countries. Our study also showed a significant geographical transition of metals primary production from the developed economies such as USA and Russia to rapidly growing economies such as China over the last two decades. However, looking at the current geological reserves of the metals considered in this study, it is likely that Chinese dominance will decrease over the metals primary production market in the long-term future due to changing socio-economic and regulatory condition in China, as well as development and operation of mines in other countries.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.05.118.

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